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RAPID TRANSIT SUBWAYS - MAINTENANCE AND ENGINEERING REPORT

James Birkmyer

Bechtel Incorporated
Fifty Beale Street
San Francisco CA 94119

JANUARY 1978
FINAL REPORT

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The maintenance of an underground rapid transit complex requires considerable labor, equipment, and variety of material. This analysis of the maintenance and engineering data of North American and European transit properties identifies the important technical and organizational factors that affect the economics of subway maintenance.

Water seepage in structures is a prime cause of maintenance for many installed items. Methods of repairing defective structures are described, and criteria for durability are developed for new structures. To minimize maintenance, escalators, elevators, and pumping and ventilating equipment of the highest quality must be selected and properly maintained. Station finish materials and systems that have demonstrated satisfactory service in underground stations can appreciably reduce maintenance.

Careful layout and design of details in new installations to facilitate the cleaning process will effectively reduce costs. Cleaning of the trackway and appurtenant structures is important to the functioning of the train support equipment. Trackway cleaning trains are being used increasingly.

Present worth cost analyses comparing installed costs versus maintenance costs provide valuable assistance in evaluating alternative selection of most subway items.

The report presents the data collected, identifies deficiencies, and develops good-practice solutions. Two Guidelines were compiled from the data: Maintenance of Existing Properties and New Installations.

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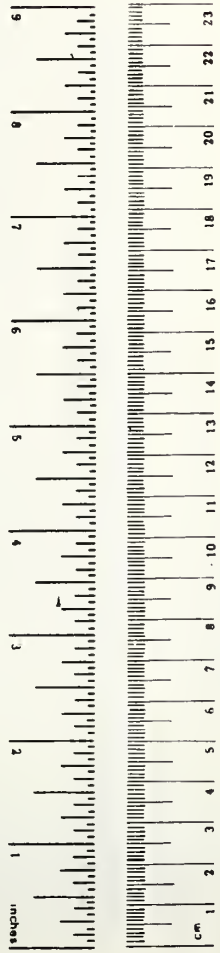
METRIC CONVERSION FACTORS

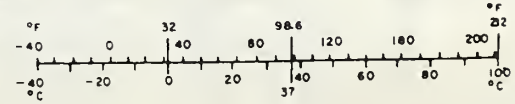
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	squsre kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teespoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	milss	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	scres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius tempersture	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

Rapid rail transportation has a pronounced impact on the lives of an important sector of mobile metropolitan dwellers. In the future, the impact promises to become greater and the sector larger. Rapid transit patronage comprises several groups: the 9-to-5 commuter, the 10-to-4 business traveler, the 10-to-4 shopping crowd, and the 7-to-midnight reveller. The first two groups use the system little on weekends, but this may be compensated for by sightseers, tourists, etc.

The success or failure of a transit system in meeting the needs of these diverse travellers is, of course, important to the transit authorities. They must be concerned with the practical aspects of transportation, such as the train service and reliability, as well as the psychological aspects, such as visual impacts, noise, and rush hour crowding — all of which are magnified by being contained underground. The effects of all these concern the transit operator because they have a marked impact upon the fare box.

The goal of most enlightened public transportation authorities is to provide fast, frequent, economic, clean, and quiet service. These service goals are generally given the full searchlight of publicity by new authorities, but they become increasingly suppressed, at least by the public relations office, under the hard realities of operating conditions and the yearly financial balance sheet. A recent consensus obtained from several public transit operators in this country and abroad indicates that these vital goals must be achieved if public transit is to be successful. It is here that appropriately designed properly-implemented maintenance procedures play their role.

In Paris, RATP, a historic property impressive in its public acceptance, has oriented both the modernization of its old Metro and the construction of its new rapid transit system to three dicta: good service, convenience, and comfort. A visitor to the Metro finds this readily apparent, both from the high standard of renovation of the older stations and the cleanliness of the system as a whole.

If U.S. public transportation systems are not to become a total burden on the taxpayers, they must provide quality service. Well maintained transit plant and equipment (the stations and trains), reliable service, and convenient access and interchanges with supplementary transportation systems are probably more important quality measures in the eyes of the public than the actual cost of the fare.

Nowhere is this requirement exemplified more than in an underground complex. Good appearance and convenience of access and movement are as essential in the underground stations as reliable, dry trackway structures are for proper functioning of the train.

The U. S. Department of Transportation has recognized the importance of all these factors in initiating this study. Its goals are to provide transit system operators with guidelines for the economic maintenance and cleaning of their underground structures, and for engineers and architects of new installations, a second set of guidelines to furnish criteria for optimizing the engineering of new structures, including recommendation of material selection and planned maintenance and cleaning programs.

The sponsor of this study was the Office of Rail Technology, Office of Technology Development and Deployment, Urban Mass Transportation Administration of the U.S. Department of Transportation. It is part of the Coordinated Department of Transportation Tunneling Program.

This work was performed under contract to the Transportation System Center (TSC) Cambridge Massachusetts. The contract was awarded under TSC's Urban Rail Supporting Technology Program with Mr. Gerald R. Saulnier of the Office of Ground Systems as technical monitor. The author wishes to thank UMTA, the sponsor and Mr. G. Saulnier of TSC for the assistance and advice provided during the execution of the work.

Early in the work schedule, the American Public Transit Association (APTA) formed a Maintenance Guideline Committee, the members of which comprised the Maintenance Superintendents of Massachusetts Bay Transportation Authority, Chicago Transit Authority, New York City Transit Authority, New York Port Authority Trans-Hudson Corporation, and Washington Metropolitan Area Transit Authority. Under the chairmanship of TDC, the committee defined maintenance areas of particular interest in ongoing operating properties. The committee also provided considerable maintenance data from represented properties and valuable constructive critiques of the Guidelines as they were being written.

Bechtel's consultants for the work were Mr. E. E. McPhail, Manager of Plant Maintenance, Toronto Transit Commission and the Maintenance Superintendents of the London Transport Executive. Both consultants drew deeply from their considerable experience in maintaining their subways and greatly assisted in formulating many of the Guidelines.

Other transit property managements who cooperated most helpfully in this work by making available both their maintenance engineering staff for onsite discussions and by providing their maintenance data, were San Francisco-BART, Paris-RATP, Stockholm-SL, Brussels-STIB, Berlin-BVG, Hamburg-HHA, and Munich-SV.

Several maintenance equipment manufacturers and contractors provided useful data about their particular equipment or operations. These included the San Francisco offices of Otis Elevator Company, Easterday Supply Corporation, Clarke-Gravely Corporation, American Colloid Company, American Building Maintenance Company, the Tile Council of America, and the National Terrazo and Mosaic Association, Inc.

For the assistance provided by these transit properties, organizations, and manufacturers, the author wishes to extend his thanks and especially to the various staff who, in spite of busy work schedules, gave their time freely to provide the information sought.

Publishers of technical material who kindly gave permission for reproducing some of their material (or referencing it) include American Concrete Institute, the Stamat Publishing Company, the Institution of Civil Engineers (London), and the Institution of Structural Engineers (London).

EXECUTIVE SUMMARY

The lifetime cost of the underground structures and fixed equipment of a transit property comprises the initial capital investment and the maintenance cost expended over its lifetime. Such maintenance is required both for the longevity and safety of the structures and for efficient and safe operation of the trains and related fixed equipment. These latter items, as well as maintenance of the public areas in the stations, affect the passengers' safety and comfort and, consequently, their attitude towards the transit system as a whole.

Transit structures may be separated into two functional areas: the trainway in which the trains are operated, and the stations which serve the passengers entering and leaving the trains. Within each of these areas, maintenance effort must be expended upon the constituent items if their installation costs and lifetime maintenance are to be optimized. The importance to the operations of a transit system of maintaining the major constituent items is discussed under the two headings of Trainway and Station.

TRAINWAY

The major trainway components to be considered are the structures and the ventilation and drainage systems.

Structures

The integrity of the underground trainway structure is vital to the reliable performance of the train because the structure supports the guideway (track), conductor rail, communication cables, and other essential train services. Any structural defects that develop may require expensive repairs that will

impair the train operating schedules. Excessive water ingress may also cause malfunction of train support services with similar interference. Therefore, it is of prime important to build the structures initially to be as maintenance free as possible and designed to minimize the impact on train operations of any maintenance which is required.

Ventilation

Shafts from underground trainway structures to the surface are normally required for four purposes: to remove excessive heat generated by the train operation; to alleviate wind in the stations caused by the movement of the trains; to control smoke in case of fire; and to provide access to the underground structures for maintenance and to serve as emergency exits for passengers. For both the removal of excess heat and the control of smoke, mechanical fans are generally provided in some or all of the vent shafts.

Proper functioning of the ventilation shafts and fans is important for the comfort and safety of the passenger. Two kinds of maintenance are required for these important systems: of the structure (e.g., concrete repair, corrosion protection of miscellaneous metal, and periodic cleaning of the shaft) and of the mechanical and electrical components of the fans.

Drainage System

The subway drainage system comprises collectors (trackway gutters, catch basins, and piping) and the pumping complex (the pump structure, sump, and pumps).

Underground structures are potential collectors of groundwater, of surface water runoff, and of water from burst water mains. The system may be flooded by these aquifiers, particularly the latter two, in such circumstances as clogged collecting systems and sumps, pump failures,

or a combination. Such occurrences will disrupt train schedules to the inconvenience and even danger of the passenger. Systematic inspection and maintenance of all the elements of the drainage system are required to reduce or eliminate altogether the danger of flooding.

Cleaning of the Trackway

Regular cleaning of the trackway is required for the proper functioning of the train control equipment and to reduce the incidence of maintenance of fixed mechanical equipment and the drainage system.

STATIONS

The underground station, the vital link for passengers between the street and train, comprises several major items whose maintenance affects the operation of the transit system and the safety of the passengers. These items and their maintenance requirements are described in the following paragraphs.

Structures

The integrity of the structure is important for satisfactory performance from the architectural finishes, lights, and fixed mechanical equipment. Structural cracks, especially if they allow water seepage or dampness, are potentially damaging to all three items and particularly mar the appearance of the architectural finish. Additionally, cracks may create hazards to pedestrians.

Escalators

It is becoming a common practice worldwide to use escalators as the major means of moving people vertically in underground stations. In typical transit properties, several escalators are installed per station, which may result in a total number of 200 or 300 in large properties.

An escalator breakdown in a busy station during rush hours will seriously reduce the vertical movement of passengers, causing not only inconvenience but dangerous overcrowding on the mezzanine and platform areas. Also, mechanical faults which may cause sudden stops and starts or excessive wear of moving parts create conditions which may cause accidents.

Rigorous methods of inspection and maintenance must be instituted on all the components of the escalators if such undesirable situations are to be avoided. Engineers in all transit properties seem to be conscious of this factor, and generally, designate a large fraction of their maintenance budgets for escalator maintenance.

Elevators

In general, elevators are a secondary means of transporting passengers, and their use appears to be restricted to very deep stations or to small elevators for use by the handicapped (particularly in the United States). Most countries of the world strictly regulate both the design and safety controls of elevators and require periodic inspection and maintenance; hence, breakdowns or accidents to passenger are infrequent. Because of the small number of elevators installed by transit properties, their maintenance requires a relatively small fraction of the budget.

Lighting

An adequate level of lighting is needed, particularly at critical areas in the public spaces of the stations. Such areas include the head and foot of stairs and escalators, entrances and passageways, and the train platforms. To maintain satisfactory illumination, the lamps and reflectors must be kept clean and the lamps replaced when they burn out. A systematic lighting maintenance program, therefore, is necessary.

Station Finishes

The floors, stairs, walls, and ceilings, especially the floors and stairs, are the major points of contact with the passenger. Unsafe conditions can develop from an accumulation of dirt, accidental spilling of food or other substances, and wetness from various sources; additionally, wear and tear create uneven or rough surfaces which are, particularly on stairs, hazardous to the pedestrians.

Walls and ceilings are of secondary importance to passenger safety but are of prime importance to the appearance of the station and in suppressing noise, both of which functions affect the passenger and his attitude toward the system.

Maintenance within the station, therefore, consists of two activities: cleaning pedestrian areas, walls, and ceilings; and periodic repair and replacement of these items.

IMPORTANCE OF MAINTENANCE

The foregoing discussion emphasizes the important bearing which maintenance of underground structures and their constituent items has on the efficient operation of the transit system as a whole. This effect is fully appreciated by most transit maintenance engineers, although they are often hampered by budget restrictions in their efforts to undertake effective programs. Such restrictions lead to deferred maintenance which, in the end, reduces the effectiveness of the service and, consequently, the public's acceptance.

The degree of maintenance necessary for any one property to maximize its transit operations depends on a large number of variables including the age of the system and the quality of the maintainable items. Required maintenance (including the item replacement costs) can be assumed to increase with the age of the system.

Engineers in Toronto, a well maintained, comparatively new and small system, estimate that out of their total operating budget, about 11 percent is spent on the maintenance of the subway structures and installed items (discussed above), 75 percent of which is required for the subway cleaning program alone.

Older than Toronto, Chicago is also a well maintained property. The maintenance of its subway complex (including a substantial proportion of at-grade structures) is estimated to be 9 percent of the total operating cost with 55 percent of that attributed to cleaning.

One approach to establishing the desirable maintenance effort develops the present worth cost values for each maintainable item and integrates the individual efforts with the total maintenance program. In actual practice, compromises may have to be made in some of the item maintenances to satisfy the efficiency of the overall program. This philosophy is reflected in the development of the material in the ensuing report and the two sets of guidelines which are compiled from it.

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1 SUMMARY

This report describes the approach used to gather, process, and analyze the maintenance data and other information obtained from operating transit properties, engineering specialists, equipment suppliers, and material manufacturers to formulate the Maintenance Guidelines. A summary of the report follows.

SECTION 2 – STUDY APPROACH

To aid in the selection of transit properties that could provide the appropriate maintenance information, data and statistics – including size, age, and construction – were compiled for all major North American and European transit properties. Six in the former and seven in the latter countries were selected, and they agreed to cooperate in the study.

Questionnaires were sent to these properties, followed by visits from the project engineer. During the visits, information was recorded both in discussion with the transit maintenance staffs and by direct observation of the transit structures. The material gathering was oriented towards identifying the major areas of maintenance, including deficiencies, maintenance procedures and organizations, and good engineering design practices that minimize maintenance.

SECTION 3 – TECHNICAL DATA FROM TRANSIT PROPERTIES

The data obtained is categorized in four major groups, the items of which are displayed either in matrices or narrative, according to degree

of detail that was made available. The groups were structures, fixed equipment, architectural finishes, and trackway cleaning. The itemized information displayed may be briefly summarized as follows.

Structures

For both stations and trackways, base information is separated for cut-and-cover and for tunnel construction. Data include structures, type, age, geology, waterproofing, leakage, inspection, and repair.

Fixed Equipment

This comprises pumps, fans, escalators, elevators, and lights. The data include:

> For pumps and fans — location, capacity, type, operational mode, cleaning, and maintenance,
>
> For escalators — number, height, type of controls, and labor and schedules for maintenance and cleaning,
>
> For elevators — number, type, and maintenance details, and
>
> For lighting — type, cleaning frequency, and replacement frequency and procedures.

Architectural Finishes

This covers floors, walls, ceilings, and stair treads. The data generally include: material description, cleaning and washing methods and schedules, repairs, and performances.

Trackway Cleaning

Dust and debris removal methods and frequencies are displayed in a matrix, details by dust generation and composition are provided, and details are given of the vacuum cleaning train being developed by London and the high pressure water spray train used by New York NYCTA.

SECTION 4 – DEFICIENCIES IN STRUCTURES, FIXED EQUIPMENT, AND STATION LAYOUT

Deficiencies are identified in the design details and materials of the subway structures and their constituent items. Unsatisfactory station spaces and layouts are discussed. The underlying causes of the deficiencies and the resulting effects upon the principal maintainable items are examined in detail.

Structures

Some of the major defects in structures were: cracking and spalling of concrete and defective waterproofing. Both of these conditions result in water seepage and, consequently, corrosion of metallic items, interference with electrical and mechanical equipment, and provision of paths for stray electrical currents. Water seepage and cracking of the structure cause architectural finishes to deteriorate considerably.

Drainage and Ventilation Facilities

These facilities were often found to be poorly planned in regard to accesses, maintaining the equipment, and cleaning the sumps and shafts. Collection systems clogged because of deficient drainage details.

Mechanical Equipment

Deficiencies in mechanical equipment were mostly related to the tendency in some properties to install oversized pumps and to use escalators and elevators for the heavy duty service required in subway station service. Lights often suffered from corrosion and vandalism.

Architectural Finish Defects

Defects in floors and stairs chiefly stemmed from material not selected for maximum life or ease of replacement in areas of heavy wear. Defective installation details gave rise to cracking, and poor choice of color and texture made cleaning difficult.

Walls

Some materials were unsatisfactory in resisting vandalism and were difficult to clean. False wall systems not provided with the means for inspecting structures behind and lack of ventilation between false wall and structure allowed damage from structural cracking and water seepage.

Doors

Doors were sometimes not designed for the heavy duty service requirements of station and trackway.

Ceilings

Most of the defects noted for walls applied for ceilings.

General

Finish material often was not selected (or stockpiled) to permit matching of future replacements.

SECTION 5 – ENGINEERING DESIGN PRACTICES TO MINIMIZE MAINTENANCE OF STRUCTURES AND ARCHITECTURAL FINISHES

This section describes and discusses the design criteria, details, and pertinent construction procedures needed to design and install a subway complex to minimize the deficiencies identified in Section 4 and subsequent maintenance costs.

The more important items addressed are:

> Structures: Loading criteria, stresses, structural details, and concrete specifications to minimize cracking. Waterproofing membrane systems for cut-and-cover systems and caulking systems for segmented tunnel liners. Corrosion monitoring and cathodic protection of structures and the protection of miscellaneous exposed steel,

Architectural Finishes: Criteria for selecting and installing durable and easy to clean and replace materials. Details to reduce maintenance and facility replacement and ease cleaning, and

Layout of Station Areas: Requirements for ready surveillance to reduce vandalism; facilities for maintenance and janitorial equipment, materials, and personnel.

SECTION 6 – ECONOMIC EVALUATION TO OPTIMIZE ENGINEERING DESIGN DECISIONS

To assist the economic design of the subway complex, the cost benefits of alternative choices for most of the items in a subway complex should be analyzed. The methodology of performing the analyses using the present worth cost method is described and illustrated with three evaluation examples – cathodic protection systems, structural waterproofing, and floor finishes. For these, costs are estimated for installation, operation (where applicable), maintenance, and periodic replacement of the various items of the alternatives. Anticipated future expenditures were discounted to present value costs to arrive at comparative total costs of the alternatives.

SECTION 7 – MAINTENANCE ORGANIZATIONS AND PROCEDURES

An interaction chart is presented to indicate the variable factors that determine the size and composition of the maintenance and cleaning organizations for any one transit property. The major variables are: labor conditions and "other maintenance schedules," age, size, geography, and train schedules; and the structural system, materials, groundwater, and geology.

The task organization flow charts, in some properties for general operations and the subway maintenance and in others for the latter activities only, are displayed and discussed.

The various maintenance and cleaning activities were performed either by the owners' staff or by contract – the choice being largely determined by the applicable variables discussed above. The type, complexity, and amount of work included were important and sometimes overriding considerations.

Work force compositions and their geographic dispositions (over the transit system) are indicated for the properties for whom this information was made available in sufficient detail. The work forces for all properties comprised numerous trades or craftsmen who generally operate in a varying number of task forces according to the size of the property.

2 STUDY APPROACH

The essential tasks in this study of underground transit system structures both in this country and abroad were:

To gather maintenance and structure information from each property,

To study and analyze the information received, and

To determine the relationships of maintenance costs to installation costs, and, hence, identify inefficiency.

The successful completion of these tasks should establish good engineering design practices for new underground installations and optimized maintenance procedures for both new and existing properties. The study was to result in two publications: guidelines for maintenance of existing properties and a designers handbook for new installations.

SELECTION OF PROPERTIES TO VISIT

Information was to be gathered from several properties in North America and overseas. The first step in selecting properties to visit was to assemble statistical data about the most important transit properties in the world. For this purpose, 10 properties were identified in North America, 11 in Europe, and 3 in Japan. The data included route lengths, number of lines and stations operated, age of system, number of trains operated, the train capacity, and construction and equipment details. These statistics are compiled in Appendix A.

It was decided that a tentative selection of the properties should provide a mix of age and size; size being roughly determined by the route miles

operated and number of stations. This resulted in identifying the following categories and properties:

Large	Medium	Small
New York City Transit Authority	Chicago	New York Port Authority
London	Berlin	Toronto
Paris	San Francisco	Brussels
Tokyo	Boston	Munich
	Stockholm	

DOT/TSC agreed to this selection and accordingly, the properties, with the exception of Tokyo, were contacted and all signified their willingness to cooperate in providing the information.

INFORMATION GATHERING METHODS

It was anticipated that the required information from the transit properties could be recorded on coded sheets and for this purpose for each area of maintenance, such as structures, stations, installed equipment, organizational and operating information, etc., appropriate items were identified. Additionally, the sheets would be designed with the items for each area coded, to permit direct key punch recording for computer analysis.

Examination of this approach showed it to be too complex and costly for the accuracy and quantity of information that the properties probably would be prepared to provide. Hence, this method was abandoned, and questionnaire forms were developed for written recording. Examples of the forms for the first method and that finally adopted appear in Appendices B and C.

Before the visits were made, questionnaires were sent to the properties, together with examples of completed forms. Those sent to Paris and the three properties in Germany were translated into the appropriate language.

Bechtel's Project Engineer visited the seven properties in Europe the latter part of November and the early part of December 1975; most of the U.S. properties were visited in January and February 1976. The DOT/TSC Technical Administrator, Mr. G. Saulnier, was present during the visits to Boston and Chicago.

Generally, one or two days were required to gather the information from each property. The data sheets, with the exception of the one for Brussels, were not completed by the properties' operators; however, they did provide useful advance notice of the type of information being sought. In general, the bulk of the information was received by direct questioning of the properties' maintenance or design staff, from direct observation in touring the system or shops, and from examination of drawings and details in the properties' engineering offices.

The personnel at all properties were very cooperative, but some had neither the time nor the staff available to provide much of the detailed information requested at the time of the visit. Some of this information was subsequently requested by letter, and a portion of it was received.

IDENTIFICATION OF MAJOR AREAS OF MAINTENANCE AND DEFICIENT DESIGN DETAILS

Discussion with the maintenance staffs and review of the composition of the work maintenance teams, together with a study of the information provided, identified areas where the major maintenance effort was expended and items and design details that proved the most troublesome and how they might be improved. The maintenance engineers generally had very definite opinions on these subjects.

STUDY OF MAINTENANCE PROCEDURES AND ORGANIZATIONS

Staff of most properties outlined their several organizations that accomplished the different types of maintenance needed in that property. In

general, it was difficult to obtain anything more than estimates of the labor required for typical maintenance operations. Information obtained included the impact of train scheduling and the constraints exercised by other maintenance operations on the maintenance of the subways.

ESTABLISH GOOD ENGINEERING DESIGN PRACTICES

To optimize capital installation with maintenance costs, information received from the transit properties was studied to locate most of the major maintenance areas and items, identify inefficiencies, and to recommend remedies. Part of this work required contacting manufacturers of maintenance and cleaning equipment and soliciting their opinions about the most effective application of their products. Cost studies and economic analyses were undertaken on several subjects, including waterproofing systems, cathodic protection systems, and architectural finishes.

GUIDELINES FOR EXISTING PROPERTIES

These were developed first by identifying how items exercise restraints upon the related maintenance, the various maintenance generants in any or all properties, and how these interact upon maintenance procedures and organizations. These identifications provided the qualifications of the maintenance guidelines for the individual items.

GUIDELINES FOR NEW INSTALLATIONS

From a study of the experience and history of the existing properties visited, the requirements for service life for underground structures and the contained station finishes and equipment were established. With this as a point of departure, guidelines were written for the design of most major items and components. A good deal of input for these was drawn from Section 2, Service Conditions and General Criteria.

3 TECHNICAL DATA FROM TRANSIT PROPERTIES

The information and data obtained during visits to the transit properties comprise records of discussions with transit personnel during onsite interviews and printed material provided during the visits, including descriptive literature, annual reports, technical articles, and organizational charts and drawings, etc. The recorded information has been compiled in three formats:

Narrative descriptions of sequential property items,

Matrices displaying data for individual items for all properties, and

Narrative gathered from all properties, if data are inadequate for matrix display.

The following discussion indicates the adequacy of the information gathered, provides some conclusions, and identifies some of the more important maintenance efforts for the underground complexes.

PROPERTY INFORMATION

This information (contained in detail in Appendix 2.4) was obtained in discussion with the engineers responsible for the three maintenance groups: structures, installed equipment, and architectural finishes. Information for the various maintenance types and items within these groups was fairly adequate for most of the transit properties visited; however, information on overall maintenance organizations and costs was generally deficient. The maintenance personnel interviewed did not have ready access to this information, nor did it appear to be readily

available from transit organizations in the form requested. The maintenance engineers did provide information about the effort (generally in manhours) needed to maintain the principal items.

Subsequent to site visits, the majority of transit organizations visited were requested by correspondence to supply additional information concerning the proportion of maintenance effort in the underground portion of their system to the total operating effort, including maintenance costs; the material obtained from these requests is incorporated as appropriate in the relevant sections.

DATA MATRICES

Matrices were developed to permit comparative evaluations of the data received, as indicated in Figures 3-1 through 3-9. In general, each matrix has provision for sixteen bits of information for each item — eight for original installations and eight for recent installations. The purpose of the two headings is to indicate the trend of changes in materials used and certain other items.

To evaluate the significance of the material gathered, the more important aspects of detailed information are reviewed for each group and maintenance item.

UNDERGROUND STRUCTURES

Figure 3-1 is a matrix relating the major underground structural components of the 13 properties surveyed. The information is classified by structure identification (station or trackway) and installation method (cut-and-cover or tunnel); each classification is further subdivided by the structural system used.

For both stations and trackways, the structural system may be any of the following:

Monolithic – reinforced concrete, (generally) rigid frame construction, with structural members of either beams and slabs, and columns or slabs, only

Articulated – here the walls are normally constructed from the surface down by the slurry concrete wall method or the secant pile method; horizontal structural members often have nonrigid connections where they meet the walls,

Jack arch – structural steel beams in the roof, and sometimes the wall as well, with reinforced concrete spanning between the steel members, and

Tunnel – description is by the material of the structural lining: cast iron, precast concrete, and boltless relate to segmented linings. Other linings are segmented/secondary concrete and rib-and-lagging/concrete.

The legend at the bottom of the page decodes that data contained in the eight-bit box for each item. The following paragraphs describe the more important highlights of the matrix:

The age of the older systems is more than 75 years (it should be noted in this respect that the information obtained for New York City Transit Authority (NYCTA) is for the Independent System, constructed by the City of New York 35 years after the other two privately constructed systems were in operation,

Most of these structures were constructed in soft ground with high water tables (Stockholm, predominantly constructed in rock, is an exception),

Without exception, some type of roof waterproofing was provided for cut-and-cover structures; at several of the transit properties, particularly those located overseas, the structure is waterproofed all around. Reasons given for this were protection of equipment and finishes and protection of both transit and other structures from the effects of stray electric currents,

With the exception of NYCTA, jack arch systems are no longer used in new construction of cut-and-cover structures. In bad ground conditions, slurry wall or similar construction systems are gaining acceptance,

STRUCTURE / PROPERTIES		STATIONS																TRACKWAYS																							
		CUT-AND-COVER												TUNNEL				CUT-AND-COVER												TUNNEL											
		MONOLITHIC OR OTHER				ARTICULATED				JACK ARCH				CAST IRON* SHOTCRETE+ PC†				MONOLITHIC OR OTHER				ARTICULATED				JACK ARCH				CAST IRON				MASONRY				PC CONCRETE				SEGMENTED WITH SECONDARY P.C.				BOLTLESS				CONCRETE				SHOTCRETE			
LONDON	O	70	S	M/R	12					70	S	M/R	12	55*	S	C	72	70	S	M/R	12					70	S	M/R	12	55	S	C	72					35	S	C/A	12																
		8	5	M	M					8	5	M	M	80	10	S	S	15	10	M	M					15	10	M	M	85	5	S	S					50	15	M	M																
	R	1	S	M/R		1	S	M/R						1	S	C						1	S	M/R																		20	S	N	72								
		5	3	N		5	3	N						50	0	N						5	3	N																		50	0	S	S								
PARIS	O	70	S	M/A	12					70	S	M/R	12					70	S	M/A	12													70	S	N	12																
		8	5	M	H					8	0	M	H					12	3	M	H													25	0	S	H																
	R	5	S	M/W	12																																	5	S	C/A	12														
		70	50	S	S																																	70	50	M	S														
STOCKHOLM	O	25	S/R	M/A	12									20+	R	N	12																									25								20	S	M	12	25	R	N	12
		15	10	N	S									60	0	S	S																															40	30	N	N	50	0	M	M
	R																																																							
BRUSSELS	O	2	S	M/W		2	S	M/R										2	S	M/W		2	S	M/R														2	S	C/A										2	R	N					
		4	0	N		20	15	S										10	5	S		30	20	S														40	25	S										100	20	N/A					
	R																																																					
HAMBURG	O	20	S	M/A	12					65	S	M/A	12	65*	S	C/L	12	20	S	M/A	12					65	S	M/A	12	50	S	C/L	12																						
		8	5	N	S					8	5	N	S	60	55	S	S	8	5	N	S					8	5	N	S	25	45	N	S																						
	R																																																				
BERLIN	O									70	S	M/A										70	S	M/A																														
										10	5	N	S									20	15	N	S																														
	R	20	S	M/R														20	S	M/R																																		
		15	10	N														15	10	N																																		
MUNICH	O	5	S	M/A	12									5†	S	M/A	12																					5	S	M	12	5	S	M/A	12								
		20	10	N										30	20	N																						50	30	N		50	30	N									
	R																																					1	S	G													
																																						60	30	N													

Figure 3-1. UNDERGROUND STRUCTURES MATRIX

STRUCTURE / PROPERTIES		STATIONS												TRACKWAYS																	
		CUT-AND-COVER									TUNNEL			CUT-AND-COVER								TUNNEL									
		MONOLITHIC OR OTHER				ARTICULATED				JACK ARCH				CAST IRON* SHOTCRETE+ PC†				MONOLITHIC OR OTHER				ARTICULATED				JACK ARCH				CAST IRON			
TOKYO	O																														
	R																														
TORONTO	O	22	S	M/R	12													17	S	C/L	12									17	S	C/L	12
		8	4	S	S													40	30	S	S									40	30	N	S
	R																														
SAN FRANCISCO	O	5	S	M/R	6	5	S	M/R	6									5	S	M/R	6												
		10	6	S	S	8	4	S	S									20	12	S	S												
	R																														
CHICAGO	O	40	S	M/R	6																										
		12	4	S	S																										
	R	5																5	S	M/R											
																		15	10	N											
BOSTON	O									75	S	M/A	12													75	S	M/A	12	50	S	C/L	12
										8	0	S	M													10	2	S	S	50	40	S	S
	R	5	S	M/A	12													5	S	M/A	12												
		8	0															10	2	N													
NEW YORK PATH	O	65	S	M/A	24													65	S	M/A	24									65	S	C/L	24
		10	6	S	S													15	10	S	S									50	30	S	S
	R																														
NEW YORK CTA	O									40	S	M/A	6													40	S	M/A	6	40	S	C/L	6
										10	4	S	S													25	10	S	S	60	50	S	S
	R									10	S	M/R	6													10	S	M/R	6				
										10	4	M	S													25	10	M	S				

STRUCTURE / PROPERTIES		TRACKWAYS																			
		TUNNEL																			
		CAST IRON				MASONRY				PC CONCRETE				SEGMENTED WITH SECONDARY P.C.		BOLTLESS		CONCRETE				SHOTCRETE			
TOKYO	O																				
	R																				
TORONTO	O																				
	R									6	S	C/A	12								
										60	25	H	M								
SAN FRANCISCO	O	5	S	C/L	6													5	R	N	6
		50	40	S	S													75	10	S	S
	R																				
CHICAGO	O																				
	R																	40	S	N	6
																		30	10	M	M
BOSTON	O																				
	R																				
NEW YORK PATH	O																	10	5	M/A	–
																		48	40	S	S
	R																				
NEW YORK CTA	O																				
	R																				

LEGEND:

O = ORIGINAL
R = RECENT

1	3	5	7
2	4	6	8

1. AGE (1976) – YEARS (AVERAGE) SINCE START OF SERVICE
2. DEPTH OF ROOF IN FT BELOW GROUND SURFACE
3. GROUND
   S = SOFT
   R = ROCK
4. WATER TABLE
   FT ABOVE ROOF
5. WATER PROOFING
   N = NONE
   TYPE/COVERAGE M/R = MEMBRANE/ROOF
   M/W = MEMBRANE/ROOF AND WALLS
   M/A = MEMBRANE/ALL AROUND
   C/L = CAULKING LEAD
   C/A = CAULKING/ASBESTOS CEMENT
6. LEAKAGE INCIDENCE
   S = SLIGHT
   M = MODERATE
   H = HEAVY
7. INSPECTION FREQUENCY
   MONTHS
8. REPAIR EFFORT
   S = SLIGHT
   M = MODERATE
   H = HEAVY

Figure 3-1. (CONTINUED)

In tunnel construction, cast iron lined tunnels have demonstrated low maintenance costs over 75 years. There were few examples of precast concrete segmented single linings; most of these were in London, including one installation with bolted channel section segments which has given reasonably satisfactory service in wet ground for 35 years. Boltless concrete precast segments, pioneered in London 20 years ago, have been and probably will continue to be used there in dry ground. In Munich, tunnels using gasketed precast concrete segments have recently been constructed with apparent success in ground with high water tables. This is the first time precast concrete has been used in Germany without an inner waterproofing membrane with a secondary concrete lining, and

Shotcrete is employed extensively in the Stockholm system for lining rock tunnels and appears to provide considerable economy. Maintenance effort is required, however, to inspect and repair spalled areas and to divert leaks and seepages.

The major maintenance effort in underground structures relates to water ingress. Properties such as those at Berlin and Hamburg in Germany and NYCTA and PATH in the New York-New Jersey Area where the structures are waterproofed all around, have up until now required virtually no structural repairs. Until recently, the Paris system, which was similarly waterproofed, required little maintenance. Over the years, however, the waterproofing disintegrated, and now a heavy maintenance program is being undertaken to refurbish the leaking structures. San Francisco's comparatively new system is constructed mostly in variable ground with high water tables. Most of the structural maintenance required so far has been related to water seepage, particularly in areas of bad ground. Some reconstruction and deep well dewatering are being instituted by the NYCTA capital program.

On the whole, maintenance of structures appears to be a small part of the present maintenance budgets for transit properties, although, as the problem with the Paris system indicates, this is very likely time-dependent.

None of the transit organizations visited, with the exception of that in San Francisco, had used nondestructive testing methods for determining the integrity of structures on the earth face. Generally, a visual maintenance inspection for cracking, corrosion, water ingress, etc., was undertaken. San Francisco, with severe corrosive conditions in some areas, was the only location where metallic (steel) tunnel liners were electrically bonded to provide for possible future installation of cathodic protection. In one tunnel section the liners are also actively monitored for corrosion.

FIXED EQUIPMENT

Pumps

The transit organizations provided fairly comprehensive information of a general nature about their line structure pump installations, but this information does not lend itself to a useful matrix. Therefore, the data collected from each property are summarized in the following paragraphs.

London. A total of 462 pumps are installed in the subway system. Since 1963, the policy has been to install a minimum of two pumps per trackway location; large stations have three pumps. An alternative power source is provided. The recent trend is to use "Flyght" submersible pumps is three sizes: 3 hp, 12 hp, and 22 hp, with a maximum weight of 400 pounds. These pumps are mostly automatic, although some are manually operated. The pumps are sized for seepage; discharge is generally into adjacent sewers. Systemwide, 12 million gallons of water from seepage are pumped each week.

A staff of 67 is engaged in pump maintenance and repair; normally, one man inspects 12 to 14 pumps each day. The Permanent Way Department is responsible for cleaning the pump sumps.

Paris. In the trackway system, two pumps for seepage control are typically located at low points between the stations. Twenty standby mobile pumps, with two surface trailers, are kept in readiness for emergencies. In addition, the city fire department provides backup assistance if serious flooding occurs. The Urban Metro System pumps 3,200,000 m^3/year of water and the Rapid Transit System 210,000; these figures include seepage and station drainage.

Stockholm. Pumps are provided at both ends of each station and at intermediate points in the trackways. The pump sumps have two pumps that cycle alternately. In addition, emergency portable pumps are placed at three locations in the system. Diesel electric standby generators are located in alternate stations and are test run every month. These standbys serve the elevators and lights as well as the pumps.

In the opinion of the engineers at this property, the pumps are too large for the day-to-day service required for pumping seepage water. The pumps are inspected and test run every two weeks.

Brussels. Two pumps are placed in the lowest points at each location. They are sized to handle normal infiltration and also appear to double for sewage removal. In the North South line, where there is a flooding probability, additional pumping capacity is provided. There is no policy concerning mobile pumps, reliance being placed on the City Fire Department.

Suppliers provide the maintenance service. Pumps are cleaned once yearly, and their operation is monitored by station masters.

Berlin. Because of the almost completely water tightness of the system, the pumps placed in the low points of the trackways to handle emergencies are seldom operated. Two pumps are installed at each station for station drainage. The pumps are self-lubricating and centrifugal, with capaci-

ties of 5 to 30 m^3/hour. Apparently, the pumps are inspected and test run approximately every six months.

Hamburg. The system uses a total of 200 pumps with an average head of 15 meters. One man working full time performs all the routine maintenance.

Munich. The pumps used in this system are quite small. Two are provided at each station and also in the lowest section of the line structure. Because the cut-and-cover structures that predominate are completely waterproofed, as are most of the tunnels, water ingress is slight. One standby mobile pump unit is provided and has been used twice to cope with water from broken water pipes on the surface.

Toronto. Two types of pumps are used — submersible and shaft driven. The former are used only where a drive shaft would have to be longer than 20 feet, a length that would require additional maintenance. Both types of pumps appear to give equally reliable service. Two pumps of equal size are installed in each sump. The high water level alarm system is monitored by the transit system controller.

Typically, sumps are cleaned out yearly, and pumps are inspected weekly, a process that involves lubrication and a performance check of float controls. A pressure gauge check is made at 3- to 6-month intervals.

San Francisco. Each of the 26 sumps in the system is equipped with two 15 to 20 hp pumps. One of the two pumps in each sump substitutes for the other in case of failure. The average pump lift is approximately 50 feet. Most pumps run in intermittent service. The pumps are designed for flooding conditions and, hence, are oversize for operational service conditions. The high capacity allows the sumps to be emptied in a relatively short time, which entails frequent stopping and starting of the pumps.

The pumps are equipped with automatic greasing devices. Four different maintenances are performed on the 52 pumps installed, and the manhours per year expended on the maintenances for all pumps are summarized below:

Type of Maintenance	Manhours
Monthly	80 mh x 12 = 960 mh/y
Quarterly	48 mh x 4 = 192 mh/y
Semiannually	80 mh x 2 = 160 mh/y
Yearly	120 mh x 1 = 120 mh/y
	Total 1,432 mh/y

This translates to approximately 27 manhours per pump per year. Sumps are cleaned at regular intervals with sludge pumps.

Chicago. The pumps are generally located between stations at low points in the trackway, two pumps being installed for each sump. The usual pump size is 15 hp, but some 25 hp and a few 40 hp ones are installed. The average pumping head is 60 feet. Pumps are controlled or monitored remotely. Nearly all the pumps have been in service for 30 years. Several manufacturers, including Chicago Pump, are represented; most of the motors are made by General Electric. The City Fire Department is relied on for emergencies; no mobile pump units are provided.

The contactors are inspected and greasing of the pumps is undertaken monthly. It is estimated that maintenance of all pumps requires less than one manyear.

Boston. In general, pumps are installed at low points in the trackway between the transit stations. The two to three pumps at each location include at least one vertical and one horizontal pump. The total number of pumps is 73. Older pumps are being replaced at a rate of approximately

three per year. New installations are hooked up to the central control stations for monitoring. Pumps are inspected daily.

New York PATH. There are 40 pumps located in low points along the system; their capacities vary from 50 to 750 gpm. Most of the pumps are very old. They were originally steam driven but later converted to compressed air, and compressed air service is installed throughout the system. At the midpoint under the river crossing, each tunnel has a pump station provided with one 150 and one 750 gpm pump. Elsewhere, two electric submersible pumps are used.

The water level in the sumps is remotely monitored by float alarms. The pump stations are inspected daily or twice daily. The pump maintenance and inspection group consists of one foreman and nine workmen. Inspection and maintenance of the air piping and discharge system are performed by the same work gang.

New York NYCTA. The sumps are located in low points of the track structure or, in some cases, conveniently near surface sewers. Pneumatically operated ejector pumps are used in the stations. Many sizes and types of pumps and sumps are used.

A typical pump station was described as: a 8- x 8- x 12-foot deep sump with one 1,500 gpm emergency pump and one 200 gpm seepage pump. Compressed air is provided in many areas of the system for the track interlocks. Many of the pumps are operated in underwater tunnels with air. These pumps are very reliable. The majority of sump pumps are electrically operated and are of special design.

No emergency standby generators are provided, reliance being placed on the power utility. Pumps are usually tied to two different power sources (e.g., from either side in the street above). The firm of Fredricks manufactured many of the early installed pumps.

Inspection is performed weekly; one man is responsible for 30 to 40 pump locations. He regularly checks the inflow and amount of silt buildup, and also undertakes some drain cleaning. A permanent, four man gang cleans the sumps of silt, sand, and junk, which is then bagged and removed by the work train. There is no access from the sump pump to the surface.

Wet or dry mains are provided in the trackways of the under river tunnels with 1 -1/2 inch hydrants at approximately 200-foot centers. Fire hoses are provided. New construction will be provided with wet water lines throughout the trackways.

Some general conclusions may be drawn:

> As would be expected, at transit properties in Europe where complete waterproofing has been installed around the transit system structures, pumping requirements are minimal, with little maintenance needed. Pumps are provided at low points principally for emergency use,
>
> For partially waterproofed structures, which may have appreciable water seepage, pairs of pumps in a single sump are usually operated on a cycling basis. Typically, pump maintenance is required monthly. Installation of automatic oiling reduces maintenance inspection requirements,
>
> Many properties install remote monitoring for pump functioning and high water alarm, and
>
> Most pumps appear to be very reliable; maintenance and inspection are a relatively minor cost item.

Fans

The matrix for this item is shown in Figure 3-2. Two areas of maintenance are covered: the characteristics of the ventilation fan and its maintenance; and the location of the ventilation grille at or above the ground and its impact on the cleaning of the shaft. The detailed information received was somewhat spotty, but a review of the matrix and the property data leads to the following conclusions:

DATA SUMMARY		VENTILATION								
PROPERTIES[1]		LOCATION		FAN (HP/CFM)	OPERATION		CON-TROL[6]	SHAFT CLEAN-ING[7]	FAN MAINTE-NANCE[8]	
		SHAFT[2]	GRATING[3]		FRE-QUENCY[4]	MODE[5]				
EUROPE	LONDON	I/E	A	27/1,962	C	E	R	3-7-10	1	
	PARIS	I/E	A	25-30/ 2,112	S/C [9]	R	A		1	
	STOCKHOLM	I/E	A	N[10]	–	R	–	–	–	
	BRUSSELS	–	S	N	–	–	–	–	–	
	BERLIN	I	S	N	–	–	–	–	–	
	HAMBURG	I	S	N	–	–	–	–	–	
	MUNICH	I/E [11]	S	N						
NORTH AMERICA	TORONTO	I/E	I=A E=S	15 TO 35	S/E	E/R*	R	1	1	
	SAN FRANCISCO	I/E	S	80/	E	R	R	(every 2 wks) 0.038	1	
	CHICAGO	I/E [12]	S	15-20/	E	R	R	1	1	
	BOSTON	I	S	(13)	–	–	–	–	–	
	NY-PATH	I/E	S	–	E [14]	R [14]	M/R			
	NY-NYCTA	I	S	/50,000-155,000	E	R[15]	M/R	M	.25	

*R – ORIGINAL YONGE SUBWAY
E – EXHAUST ON ALL NEWER SUBWAYS

1 CITY LOCATIONS
2. I = INTERMEDIATE
E = END OF STATION
3. A = ABOVE GROUND
S = SURFACE
4 E = EMERGENCY
S = SEASONAL
C = CONTINUOUS
5. E = EXHAUST
R = REVERSIBLE
6. M = MANUAL
R = REMOTE
A = AUTOMATIC
7. INTERVAL IN YEARS
8. INTERVAL IN MONTHS
9. OPERATE 24 HOURS A DAY EXCEPT IN VERY COLD WEATHER
10. N = NOT INSTALLED
11. STATION-END SHAFT ONLY WITH TWIN-TUNNEL STRUCTURES
12. INTERMEDIATE AND PRESSURE RELIEF (BLAST) SHAFT AT MIDPOINT IN EACH STATION TRACKWAY
13. FEW INSTALLED
14. FOUR NEW FANS ARE REVERSIBLE AND FOR EMERGENCY USE
15. NEW ONES ARE REVERSIBLE; OLD ONES ARE EXTRACT TYPE

Figure 3-2. FAN MATRIX

Approximately half of the systems visited had ventilation shafts in which fans were not installed. In the remainder, the fans were for the most part operated seasonally or on a standby basis for emergency smoke control. In only one system, the deep tunneled lines in London, was there continuous operation of immediate trackway fans. In all systems except London, fan operating and maintenance costs were insignificant, and

The location of the surface ventilation grille has a significant effect on the cost of cleaning the shaft, and possibly the trackway. The London transit organization was emphatic that ventilation shafts should be terminated above street level, both for minimizing entry of dirt and for suppressing noise. Other transit organizations seemed to be divided in their opinions as to whether locating the ventilation grille in a roadway or sidewalk increased their maintenance costs significantly.

Escalators

Data gathered for this item are displayed in Figure 3-3 in a format that attempts to relate the cost and labor for maintenance to some principal characteristics of the escalators. Except for information about the labor required for inspective maintenance, the maintenance information received was very spotty.

However, some conclusions can be drawn from study of the matrix and the recorded information, as follows:

Reliable escalator operation promotes smooth functioning of the transit system and passenger safety. Escalator installation cost and annual maintenance are appreciable items in the transit system cost,

There are many variables that affect the cost of maintaining escalators. Of these, the most important are age and the distance the escalator travels annually, and

Nearly all transit organizations maintain their own escalators after the initial break-in period of one or two years, during which the manufacturer is responsible, and

DATA SUMMARY		ESCALATORS								
PROPERTIES[1]		NUMBER	HEIGHT (FT)	RUNNING CONTROL (2)	COST[3]	LABOR[4]	INSPECTION (5)	OVERHAUL[6] PERIODIC	OVERHAUL[6] MAJOR	
EUROPE	LONDON	260	40-120	R[7]	5,400	0.26[8]	7	1-1.5		
	PARIS	160	72	S/C[9]		0.56	3.5-7	1	5-7	
	STOCKHOLM	250	11-108	S		0.06		0.10		
	BRUSSELS	360[10]					(5)			
	BERLIN					0.14 0.17		2	6	
	HAMBURG	220	16-46			0.07 0.14			6-8	
	MUNICH	172				0.10[12]		1		
NORTH AMERICA	TORONTO	146	12'6" Min. TO 40'	C * R S	4,500	0.21	1 † 14	1	2	
	SAN FRANCISCO	160	18-38	C	2,400- 4,200	0.12- 0.21	7	1	5	
	CHICAGO			S	3,300[13]					
	BOSTON	60	20-50	C/S		0.23				
	NY-PATH	26	20-60		4,200	0.12- 0.16	7	1		
	NY-NYCTA	102	10-56	C		0.66	1			

120'/MIN. DURING RUSH HOUR
90'/MIN. OTHER TIMES

1 DAY INTERVAL – 5 MIN. CHECK
14 DAY INTERVAL - ESCALATOR DOWN FOR ABOUT 2 HRS.

1. C = CITY LOCATIONS
2. C = CONTINUOUS
   R = REDUCE SPEED
   S = STOP
3. $/YEAR/ESCALATOR
4. MANYEARS/ESCALATOR
5. INTERVAL IN DAYS
6. INTERVAL IN YEARS
7. REDUCED SPEED = 30 FT/MIN
8. ASSUMING LABOR EQUIVALENT $10/HR 1975
9. STOP IN UP DIRECTION ONLY
10. PROJECTED INSTALLATIONS BY END OF 1976
11. PRESENTLY UNDERTAKEN BY MANUFACTURER
12. INCLUDING 12-MONTH OVERHAUL
13. ESTIMATE COST

Figure 3-3. ESCALATOR MATRIX

It appears that the cost of escalator maintenance can be reduced by incorporating certain features in its design. These relate particularly to slowing or stopping the escalator during periods of low use, automatic oiling devices, and provision of space to ease access for maintenance and cleaning.

Elevators

Only a few transit organizations provided any detailed information on this item, partly because, with a few exceptions, more emphasis is placed by property owners on moving people by escalator than by elevator. The data received, therefore, have not been systemized in a matrix, but are summarized for each property in the following paragraphs.

London. Most of the 71 elevators installed for public use provide service for the deep stations. Early installations date back to 1907, when they were operated by attendants. These are now being replaced with electric automatic or semiautomatic installations.

Electrical maintenance is undertaken three times a month, or after 25,000 trips. Mechanical maintenance including inspection of ropes and safety gear is performed six times a month; each of these items requires a specialist section. Ropes are renewed after about 12 years with drum drive and about 8 years with friction drive. There are recorded cases of bad wear where cables have lasted as little as 3 years.

The cars are cleaned daily by the station staff, the pits monthly by a cleaning gang. The work is done at night after revenue service has ceased.

Paris. There are 19 elevator installations in the Metro system and 15 in the new deep Rapid Transit system. No provision is made for the handicapped.

Maintenance is undertaken by the escalator maintenance group; no details were provided about procedures and frequency.

Stockholm. Two types are installed: inclined and vertical. The 37 inclinced elevators, each with a capacity of eight to ten people, were manufactured in Sweden. They are installed in the same tunnels that house the escalators. The 88 vertical elevators also have capacities of eight to ten people.

The simplest type of operational system has been adopted; the majority are passenger operated. An additional 14 elevators are currently being installed in the older stations to bring the total number of vertical elevators to 100. Of the existing elevators, 64 are hydraulic. The older elevators were totally enclosed, which encouraged vandalism; future elevators will be glass sided to allow better inspection and reduce the incidence of damage.

Elevators stick on an average of once every one or two years; attempts are made to limit the duration of the stop to half an hour. Failures are normally due to malfunction of the elevator door interlocks, and when a failure occurs, a roving maintenance staff is called by a traffic controller.

Maintenance is undertaken by the owner. Comparison to the maintenance effort for escalators shows that two inclined elevators and four to five vertical hydraulic elevators require the same maintenance effort as one escalator. In all probability, electric elevators require twice the maintenance of the hydraulic type.

Brussels. No elevators are installed or being planned for public use. In future construction, elevators may be installed for service requirements only.

Berlin. There are presently no elevator installations. However, it is anticipated that elevators will be required in the future.

Hamburg. There are five elevators in the system. No details were provided, except that maintenance is troublesome.

Munich. Only the Marine Platz station has elevators for public use. No maintenance details were provided.

Toronto. Toronto is generally a high-level system, and no elevators have been installed.

San Francisco. All stations, except where the platform is at grade, have escalators for the handicapped. Both electric and hydraulic types are installed.

Preventive maintenance and repair are performed under contract by the manufacturers during the guarantee period; the owner will ultimately assume this function. The cost of maintaining the hydraulic types is anticipated to be one-half of that for the electric.

Chicago. No passenger elevators are installed in the system.

Boston. Three electric elevators were installed fairly recently. The first installation at the Quincy station experienced considerable vandalism, but this situation appears now to have corrected itself. No details on maintenance were provided.

New York PATH. Only three elevators are installed for public use, and these are two in Exchange Place station and one at the World Trade Center. Their height is approximately 70 feet and 60 feet respectively, and they are of the electric automatic type.

Incidence of vandalism is low. Seepage in the shafts requires attention.

New York NYCTA. For the entire transit system (three divisions or subsystems), there are 23 passenger elevators and 12 freight elevators. All the passenger elevators are operated by attendants to prevent vandalism.

Maintenance is undertaken by NYCTA's own staff.

The following conclusions can be drawn from studying the data:

> At older properties, e.g., London and New York, it has been found that if vandalism is to be avoided, the elevators should be operated by attendants,
>
> In Sweden, the transit organization has installed numerous small-capacity automatic elevators that have been damaged by the users. The authorities feel that adopting glass-sided cab construction to assist effective monitoring will reduce such damage,
>
> Overseas transit organizations have not yet been required to install elevators for the handicapped, as have those in the United States. In Europe and in North America, elevators do not appear to have been installed specifically to support subway maintenance operations; where installed, however, they are to some extent used for this purpose, and
>
> Hydraulic elevators require about half the maintenance effort that electric types do; the maintenance of the former however, does not appear to be a large monetary item.

Lights

Figure 3-4 presents in matrix form the information collected about lighting. It matches the type of light and its degree of protection against the frequency of cleaning, method of replacement, and frequency of replacement. The matrix, together with the information reports, indicates the following:

DATA SUMMARY		LIGHTING							
PROPERTIES[1]		TYPE[2]	COVERS[3]	LENS CLEANING FREQUENCY[4]	REPLACEMENT				REMARKS
					PROCEDURE[5]	FREQUENCY[6]			
EUROPE									
LONDON	O	I	Y	12	S				
	R	F	Y	12	S				
PARIS	O	F	Y						
	R	F	N						
STOCKHOLM	O	F	Y						BARE LAMPS
	R	F		12-14	G	12-14			
BRUSSELS	O	F							
	R								
BERLIN	O	F/I	Y	12	G	12			
	R								
HAMBURG	O	F	N	N	G	12			
	R								
MUNICH	O	F	N	N	G	12			
	R								
NORTH AMERICA									
TORONTO	O	F	Y	12	G	24 -			
	R	F	Y	12	G	24			
SAN FRANCISCO	O	F	Y	24	G	24			
	R			36					
CHICAGO	O	I							Lighting level 10-15 cf
	R	F	Y	24	S				
BOSTON	O	I							*Spotlights burn out from overheating
	R	F/I*	Y		S				
NY-PATH	O	I							
	R	F	Y	6	G	24			
NY-NYCTA	O	I							2 cf level
	R	F	N	24	S				20 cf level

1. O = ORIGINAL
   R = RECENT
2. I = INCANDESCENT
   F = FLUORESCENT
3. Y = YES
   N = NO
4. INTERVAL IN MONTHS
   N = NOT CLEANED
5. S = SPOT
   G = GROUP
6. GROUP REPLACEMENT INTERVAL IN MONTHS

Figure 3-4. LIGHTING MATRIX

There is a trend in newer properties overseas and in those being renovated to use bare flourescent lighting. Reasons given for this approach are that lighting intensity is decreased by covers and they invariably discolor and require additional time for cleaning

The European transit organizations generally follow the group method of replacing lamps, whereas those in North America invariably spot replace, a method that requires inspection.

Insulators

In properties visited, it was determined that insulators are never cleaned. In Stockholm, new clean insulators were compared to those that had been in service for a long period of time under dirty conditions No distinguishable difference was observed in the insulating properties of either type.

In one leaking section of the San Francisco subway, salts built up on the insulators to the extent that flashovers occurred. The insulators in this section are now periodically cleaned. This was the only instance recorded in which cleaning of insulators was undertaken.

ARCHITECTURAL FINISHES

Floors

Figure 3-5 identifies the various types of floor finishes used by the transit organizations in both original and recent installations. The data displayed show the maintenance procedures, including cleaning and repair, and a rough evaluation by the organization of the material's performance. The coverage detail was quite good for most transit properties, except for the items "repair" and "replacement." In many cases, where the incidence of damage or wear was generally sporadic and slight, no historical records were compiled; other installations are so new that "replacement" had not become a requirement.

DATA SUMMARY		FLOORS									FLOORS								
PROPERTIES[1]		MATERIAL[2]		CLEANING		WASHING				REMARKS	MATERIAL[2]		CLEANING		WASHING				REMARKS
		PLATFORM	MEZZANINE	TIMES PER DAY	METHOD[3]	INTERVAL (DAYS)	METHOD[3]	REPAIRS[4] PER YEAR	PERFORM-ANCE (5)		PLATFORM	MEZZANINE	TIMES PER DAY	METHOD[3]	INTERVAL (DAYS)	METHOD[3]	REPAIRS[4] PER YEAR	PERFORM-ANCE (5)	
EUROPE																			
LONDON	O	MC	MC	1	M	7	M				T	T	1	M	7	M	7-12	F	
	R	QT	QT	1	M	7	M	7-12	G		T	T	1	M	7	M	20*	G	*Anticipated
PARIS	O										T								
	R										T								
STOCKHOLM	O	QT	QT	2	M	3-7	M		G			T	3	M	3-7	M		G	
	R																		
BRUSSELS	O	–	–	–	–	–	–				–	–	–	–	–	–			
	R	QT*	QT*	1	M/E	730	E		G	*Mosaic	T	T	1	M/E	730	E		P	Not liked
BERLIN	O										–	–	–	–	–	–			
	R										T	T	1-2	M/E	–	–	–	P	Not liked
HAMBURG	O										–	–	–	–	–	–			
	R										T		1	M/E	90	M/E			
MUNICH	O										*	–	1	M/E	7	M/E	–	–	*Cast concrete
	R																		
NORTH AMERICA																			
TORONTO	O																		
	R	QT	QT	1-3	M	7	E												
SAN FRANCISCO	O	QT	QT	1	M	14-28	M/E		G		P	T/P	1	M	14-28	M/E/M		/G	
	R																		
CHICAGO	O	MC	QT/MC	6/1-5	M	21-28	M/E	/S											
	R		–	–		–	–												
BOSTON	O	MC	MC	1	M	14-28	M												
	R										P	P	1	M	14-28	M		G/F	
NY-PATH	O	MC	MC		M				M										
	R	MC	QT*	1	M	3-7	M		P G*			T	1	M	3-7	M		P	
NY-NYCTA	O	MC	MC	1	M	. 7	E		G			–	–	–	–	–			
	R		QT	2	M	7-21	E					P	2	M	7-21	E			

Figure 3-5. FLOOR MATRIX

DATA SUMMARY		FLOORS									FLOORS								
PROPERTIES[1]		MATERIAL[2]		CLEANING		WASHING				REMARKS	MATERIAL[2]		CLEANING		WASHING				REMARKS
		PLATFORM	MEZZANINE	TIMES PER DAY	METHOD[3]	INTERVAL (DAYS)	METHOD[3]	REPAIRS[4] PER YEAR	PERFORM-ANCE[5]		PLATFORM	MEZZANINE	TIMES PER DAY	METHOD[3]	INTERVAL (DAYS)	METHOD[3]	REPAIRS[4] PER YEAR	PERFORM-ANCE[5]	
EUROPE	LONDON O										A		1	M	–	–	–	–	
	LONDON R		R	1	M	7	E	–	F		A		1	M	7	M	1*		*In heavy traffic areas
	PARIS O		–	–	–	–	–				A	A	2	M	1	M	5*	G	* 1 year heavy
	PARIS R		R	2	M	1	M		G		MT	–	2	M	1	M	–	–	
	STOCKHOLM O										MT	MT	1-3	M	3-7	M		G	
	STOCKHOLM R		R						P	Tried; not satisfactory	–	MT*	3	M	3-7	M		G	*Large stone good
	BRUSSELS O	–	–	–	–		–	–	–		–	–	–	–	–	–			
	BRUSSELS R	R	R	1	M/E		E		G		MT	MT	1	M/E	730	E		P	Not liked
	BERLIN O										A	A	1-2	M/E				G	
	BERLIN R										A	A	1-2	M/E	•			G	*Not washed
	HAMBURG O		–	–	–	–					A*	A*	1-2	M	00			G/F	* Replaced by terrazzo
	HAMBURG R		R	1-1½	M	90	M/E				MT	MT	1-2	M	90	M/E		F	
	MUNICH O										–	–	–	–	–	–			Very dark colors not liked
	MUNICH R										MT	M	1	M/E	7	M/E		G	
NORTH AMERICA	TORONTO O										MT	MT	1-3	M	7	E	S	F	
	TORONTO R										MT	Q/T M/T	1-3	M	7	E	S	F	
	SAN FRANCISCO O										MT	MT	1	M	14-28	M/E		P	
	SAN FRANCISCO R																		
	CHICAGO O										–	–	–	–	–	–			
	CHICAGO R										MT	MT	1-5	M	21-28	M/E			
	BOSTON O		–	–	–	–	–				–	–	–		–				
	BOSTON R		R	1	M	14-28	M		G		MT	MT	1	M	14-28	M	–	P	
	NY-PATH O		–		–						–	–	–	–	–				
	NY-PATH R	MC	R	1	M/E				F		MT	MT	1	M/E	3-7	M/E		G	
	NY-NYCTA O		–	–	–	–	–					–	–	–	–	–			
	NY-NYCTA R		R	1	M	7-21	E*			*Trial only		M	2	M	3	E		G	

1. O = ORIGINAL
   R = RECENT
2. A = ASPHALT
   MT = MONOLITHIC TERRAZZO
   OT = QUARRY TILE
   MC = MONOLITHIC CONCRETE
   T = TERRAZZO
   P = PAVER BRICK
   R = RUBBER
3. M = MANUAL
   E = EQUIPMENT
4. S = SLIGHT
5. G = GOOD
   F = FAIR
   P = POOR

Figure 3-5 (CONTINUED)

A study of the matrix indicates the following:

Terrazzo used as a monolithic topping with dividers or precast tiles appears to be a popular material in most of the recent installations. Its performance, however, was not judged satisfactory in all cases,

Quarry tiles are found satisfactory by all who install them,

Rubber, either in tile or roll form, has been used by several properties in trial installations and has received favorable comment, but it appears that further development of the material, particularly in respect to its cleaning properties, is required before it will gain general acceptance,

Floor cleaning frequencies and methods, both sweeping and washing, vary widely among transit organizations. Some of these differences are caused by the variations in passenger density and dirt loading in the stations of the different transit properties, and

In most properties, the stations are swept manually, but in many, equipment is used for periodic washing.

Walls

Figure 3-6 is similar to the matrix for floors. Except for maintenance and replacement of many materials that were of fairly recent installations, the data are fairly complete for most properties. A study of the matrix discloses the following:

Ceramic tile is one of the earliest finish materials used. Performance is judged to be very good, demonstrating satisfactory service for up to 50 years. Such tiles in various forms, sizes, and colors still appear to be the most popular wall finish materials in modern day transit station installations,

Painted concrete or plaster is an economical initial installation that appears to have given satisfactory service in a number of properties. Painting is generally required at least every 7 years to maintain a reasonable standard of appearance, and

One aspect of the wall finish construction not brought out in the matrix concerns the details of false walls. Ventilation should be provided in the space between false and structural walls. Also, many property maintenance personnel believe it is important to place removable panels in the false walls to permit inspection of the structure.

Ceilings

Figure 3-7 is also similar in format to the matrix for floors. Data input about the performance and maintenance of various materials used in the systems was rather uneven, often because of the wide variety of materials used in any one property. From a review of the data, the following is apparent:

In nearly all of the older properties, ceilings in the earlier stations were finished by painting the concrete or the applied plaster. In many stations in Paris, London, and Boston, tunneled or vaulted ceilings were tiled,

Suspended (or hung) ceilings using a large variety of materials, mostly of an acoustic nature, are popular in both old and new station construction, and

Suspended vertical baffles in several materials, including stainless steel and aluminum, are popular in some of the newer properties.

The matrix does not show that in many properties where hung ceilings are used, crawl spaces or removable panels are provided to permit inspection of the structure above.

Stair Treads

Figure 3-8 is a matrix matching the various materials used against performance, appearance, and ease of cleaning. Referring to the matrix, and to the information narrative, the following are apparent:

At older transit properties, in anticipation of heavy wear on the station stairways, cast iron nosings set

DATA SUMMARY		WALLS																		
PROPERTIES[1]		MATERIAL[2]		CLEANING		MAINTENANCE		ACCEPT-ANCE[6]		REMARKS	MATERIAL[2]		CLEANING		MAINTENANCE		ACCEPT-ANCE[6]		REMARKS
		PLATFORM/ TRACKWAY	MEZZANINE	(DAYS)	METHOD[3]	REPAIR[4]	REPLACE-MENT[5]				PLATFORM/ TRACKWAY	MEZZANINE	INTERVAL (DAYS)	METHOD[3]	REPAIR[4]	REPLACE-MENT[5]			
EUROPE	LONDON O	PP	PP	120	M		7*			*Replaster every 30 yrs									
	LONDON R																		
	PARIS O																		
	PARIS R																		
	STOCKHOLM O	PP	PP	–	–	M	–	F											
	STOCKHOLM R																		
	BRUSSELS O	EC						G				Ma							
	BRUSSELS R											B							
	BERLIN O	EC						G											
	BERLIN R																		
	HAMBURG O	PC	PC				7	F											
	HAMBURG R																		
	MUNICH O																		
	MUNICH R																		
NORTH AMERICA	TORONTO O	PP V	PP V	28	M		7 6-22	VP											
	TORONTO R	C,B,E	C,B,E	28	M			G											
	SAN FRANCISCO O	PP	PP*	90-120	M			F				Ma	7				F		
	SAN FRANCISCO R							*P				B					G		
	CHICAGO O											Ma	90	M			P		
	CHICAGO R												90-120	M					
	BOSTON O																		
	BOSTON R											B	45				G		
	NY-PATH O																		
	NY-PATH R	P		30	M		5-7	G				B	30	M			G		
	NY-NYCTA O	C	C	30	M	S		F		HEAVY REPLACEMENT IS NEEDED									
	NY-NYCTA R											B	15-30	E					

Figure 3-6. WALL MATRIX

DATA SUMMARY		WALLS																	
PROPERTIES[1]		MATERIAL[2]		CLEANING		MAINTENANCE		ACCEPT-ANCE[6]		REMARKS	MATERIAL[2]		CLEANING		MAINTENANCE		ACCEPT-ANCE[6]		REMARKS
		PLATFORM/ TRACKWAY	MEZZANINE	INTERVAL (DAYS)	METHOD[3]	REPAIR[4]	REPLACE-MENT[5]				PLATFORM/ TRACKWAY	MEZZANINE	INTERVAL (DAYS)	METHOD[3]	REPAIR[4]	REPLACE-MENT[5]			
EUROPE																			
LONDON	O										C	C	7	M		50			
	R										C	C	7	M	S		G		
PARIS	O										C	C	–	–	S	50	G		
	R		Mo	–	–	M	–	F				•	–	–	M	–			
STOCKHOLM	O										C	C	3-7				G		
	R		EM	–	–	–	–	G											
BRUSSELS	O										C	C	5*						Years
	R		Mo	5*				G		*Years									
BERLIN	O										C	C	180	M			G		
	R		PIP			M		F			C	C	180	M					
HAMBURG	O		PIP			M		F											
	R										C	C	–	–	M		F		
MUNICH	O										C	C							
	R										A	A							
NORTH AMERICA																			
TORONTO	O	E/V	E/V			M		P			C	C			5	F			8 in. x 14 in.
	R										C	C				G			4 in. x 8 in.
SAN FRANCISCO	O		S	1*	M			F		*When polished	C	C	7				G		
	R										G	G	7						
CHICAGO	O		V	90-120	M			F			C	C	90-120*	M			G		*At trackways, every 360 days
	R		E	45	M						C	C	90-120	M					
BOSTON	O										C	C	45	M			G		
	R																		
NY-PATH	O										C	C	30	M					
	R																		
NY-NYCTA	O										C	C	15-30	M			G		4¼ in. x 4¼ in.
	R										C	C	15-30	E			G		8 in. x 16 in.

1 O = ORIGINAL
R = RECENT

2. C = CERAMIC TILE
A = ASBESTOS TILE
G = GRANITE
B = BRICK
Ma = MARBLE
V = VITRIOLITE
E = ENAMEL
Mo = MOSAIC
PC = PAINTED CONCRETE OR PLASTER
EC = EXPOSED CONCRETE
EM = EXPANDED METAL
PIP = PLASTIC PANELS
S = STAINLESS STEEL
PP = PAINTED PLASTER

3. M = MANUAL
E = EQUIPMENT

4. S = SLIGHT
M = MODERATE
H = HEAVY

5. INTERVAL IN YEARS

6. G = GOOD
F = FAIR
P = POOR

Figure 3-6 (CONTINUED)

DATA SUMMARY		CEILINGS: CONCRETE									CEILINGS: BAFFLE, WAFFLE (EGG CRATE), AND TILE								
PROPERTIES[1]		TYPE[2]		CLEANING		MAINTENANCE		PERFORMANCE (6)		REMARKS	TYPE[2]		CLEANING		MAINTENANCE		PERFORMANCE (6)		REMARKS
		PLATFORM	MEZZANINE	INTERVAL (MONTHS)	METHOD[3]	REPAIR[4]	REPAINT[5]				PLATFORM	MEZZANINE	INTERVAL (MONTHS)	METHOD[3]	REPAIR[4]	REPLACE[5]			
EUROPE	LONDON O	PP		4	M		7	F					Al			X			
	LONDON R	–														–			
	PARIS O	PP	PP	–	–	–	7	F			C	C	60				G		
	PARIS R	–	–				–				S	–	–	–	–	–			
	STOCKHOLM O	B	B					G				S/C							
	STOCKHOLM R	PP	PP				7				X*	–							*
	BRUSSELS O											Al							
	BRUSSELS R											–							
	BERLIN O	PP	PP	0	0	0	10	G			–	As	0						
	BERLIN R	–	–				–				Al	–	–						
	HAMBURG O																		
	HAMBURG R																		
	MUNICH O	PP	PP*					P*				–							
	MUNICH R	–	–									Al							
NORTH AMERICA	TORONTO O	PP	PP	12	M/E	S	6	G											
	TORONTO R	PP	Pa	12	M/E	S	6	G											
	SAN FRANCISCO O		B				–	G			–	As							Plastic or acoustic panels
	SAN FRANCISCO R		Pa				4-6				Al	Pl							
	CHICAGO O		Pa				5												
	CHICAGO R						5												
	BOSTON O	PP	Ba				7	G				C	12						
	BOSTON R	–	–				–					–							
	NY-PATH O	PP		12			4	F				C	12						
	NY-PATH R		–								AC	–							
	NY-NYCTA O	PP	Ba	Never			7-10	F											
	NY-NYCTA R	–	–	–			–												

Figure 3-7. CEILING MATRIX

DATA SUMMARY		CEILINGS: SUSPENDED								
PROPERTIES[1]		TYPE[2]		CLEANING		MAINTENANCE		PER FORM-ANCE[6]		REMARKS
		PLATFORM	MEZZANINE	INTERVAL (MONTHS)	METHOD[3]	REPAIR[4]	REPLACE[5]			
EUROPE										
LONDON	O	PP	–	4	M		20			
	R	PM			M	–	–			
PARIS	O	As								
	R									
STOCKHOLM	O	AT								
	R	EM	AC							
BRUSSELS	O		AC							
	R									
BERLIN	O	AT		0						
	R		PP	0						
HAMBURG	O						7			* FORECAST FORM
	R		PM	160*			–			
MUNICH	O	PM		NOT YET						
	R		–							
NORTH AMERICA										
TORONTO	O	PM	PM	12	M/E	H	6*	P		* REPAINT
	R	AC	AC	12	M/E	S	–	G		
SAN FRANCISCO	O		PC				5	P		
	R	PM					–	F		
CHICAGO	O									
	R									
BOSTON	O	–	–				–			* WOOD FIBRE
	R	C*					7			
NY-PATH	O	AT		12						GLAZE TILE OR PAINTED ON DEMAND
	R									
NY-NYCTA	O									INSTALLED FOR ACOU-STIC TREAT-MENT TEST
	R	PM	–	NEVER						

1. O = ORIGINAL
   R = RECENT
2. PP = PLASTER AND PAINT
   B = BARE CONCRETE
   Pa = PAINT
   Al = ALUMINUM
   As = ASBESTOS
   C = CERAMIC TILE
   PM = PERFORATED METAL
   AT = ACOUSTIC TILE
   AC = ALUMINUM CHANNELS
   PC = PLASTIC CHANNELS
   PIP = PLASTIC PANELS
   PI = PLASTIC
   X = OTHER OR NO INFORMATION
   EM = EXPANDED METAL
3. M = MANUAL
   E = EQUIPMENT
4. S = SLIGHT
   M = MODERATE
   H = HEAVY
5. INTERVAL IN YEARS
6. G = GOOD
   F = FAIR
   P = POOR

Figure 3-7 (CONTINUED)

DATA SUMMARY		STAIR TREADS								
PROPERTIES[1]		MATERIAL[2] TREAD NOSING	MATERIAL[2] TREAD BASE	LIFE[3]	APPEARANCE[4]	EASE OF CLEANING[5]				REMARKS
EUROPE										
LONDON	O	CI	T	4	P	F				* Special PC nosing
	R	PC*	PC							
PARIS	O	CI	C	X	P	F				
	R	PC	X	5-10	G	F				
STOCKHOLM	O	G	X		P	H				
	R	PC	X							
BRUSSELS	O									
	R									
BERLIN	O	G	X	*	P	H				*Very long
	R	G	X							
HAMBURG	O	G	X							
	R	G	X							
MUNICH	O	PC	X	**	P	E				*Not satisfactory
	R	G*	X							**Future
NORTH AMERICA										
TORONTO	O	C	X		F	E				
	R	QT	T		G					
SAN FRANCISCO	O	T	X		F	E				
	O	B	X		F	H				
	O	QT	X			E				
	O	C	X		G	F				
CHICAGO	O	QT	C	30+	G	E				
BOSTON	O	CI	T		P	F				
	R	B	C		F	K				
	R	R	S	11+	G					
	R	C	X		F	H				
NY-PATH	O	C	C	–	F	G				*Ferrolium Poor performance
			C		F	F				
		CI*		10+						
	R	PC		P*	–	F				
NY-NYCTA	O	CI*	C		F	F				* Farrolium †
		QT	C	5-10	G	F				**Being considered
	R	R**	–	–	–	–				

† Is being replaced by epoxy

1. O = ORIGINAL
   R = RECENT
2. CI = CAST IRON/CONCRETE
   T = TERRAZZO
   QT = QUARRY TILE
   B = BRICK
   PC = PRECAST CONCRETE
   C = CONCRETE
   R = RUBBER
   G = GRANITE
   T = TIMBER
   X = NOSING AND BASE SAME
3. IN YEARS
   X = UNKNOWN
4. G = GOOD
   F = FAIR
   P = POOR
5. E = EASY
   F = FAIR
   H = HARD

Figure 3-8. STAIR TREAD MATRIX

in concrete or timber were used. Often Carborundum was incorporated in the surface of the iron; this material is still obtainable under the trade name of Ferrolium. In both new and old properties in Germany and in Stockholm, granite is found to be the most satisfactory tread material,

Both of the above materials are somewhat unattractive and difficult to clean; however, they are excellent non-slip treads,

Easily replaceable treads such as especially formulated precast concrete with metal nosings appear to provide a suitable compromise, and

The use of rubber, as recently installed in Boston, in easily replaceable units appears to have a good future.

Glass

Most of the maintenance engineers interviewed emphasized the fact that glass requires a lot of maintenance. The degree of data obtained from the properties was varied and is summarized below:

Glass is used in three principal areas in stations: to enclose information booths, at the street entrance doors, and ornamentally as barriers in dividing spaces or as skylights,

Many properties have bullet-proof glass on the attendant's booth. This can be damaged by firearms; an occasional replacement must be expected,

In some properties, glass in doors is limited to the upper half of the door only. In any case, a plastic or a wired glass should be used to reduce damage,

The remarks above also apply to glass used for aesthetic purposes, particularly when there is close contact with the public, and

Using a bubble surface glass and tinted glass reduces the amount of cleaning required to maintain a good appearance. Clear, highly polished glass requires frequent attention, especially if it is within reach of passengers.

TRAINWAY CLEANING

Trainway cleaning requires the removal of two materials of distinctly different physical and chemical characteristics: debris and dust loose and mixed with oil drippings. Most of the debris, consisting of discarded paper, packaging, cigarette butts, etc., is dropped in the station by the passengers at train platform level, and then drawn from it into the trainway during the passage of the train. Debris in the trainway is visually objectionable from the platform, but between the stations it can cause fires if allowed to accumulate and can block the drainage system.

A large proportion of dust is metallic, generated by the wear of the train wheels, brakes, and the track rails, and in recent years, particularly, has become a matter of concern for its injurious effects in two major areas:

> The performance of electrical, train control, and mechanical equipment both on the train and within the trackway and station, and
>
> Appearance of the station finishes and subsequent increase in cleaning costs.

Removing dust from the trainway is a far more complex problem than removing debris, and, consequently, the equipment required is more sophisticated and expensive. Accumulated oily dirt in the trackways must be scraped manually.

Property Information

Figure 3-9 displays in a matrix the methods and frequency of dust and dirt removal from the trainways of various transit properties. Two large properties, London and Paris, use dry systems or vacuum trains for dust removal whereas New York NYCTA and smaller properties, including Toronto and Hamburg, use a wet system or a wash train.

Property	Dust Removal		Debris Removal			
			Platform Area		Trainway	
	Method	Frequency	Method	Frequency	Method	Frequency
London	V.T.	52	M	0.5 to 1	V.T. M	52 7
Paris	V.T.	26	M	2-4	V.T.	40
Stockholm	V.T. W/M	3 52	V.T.	3	V.T.	3
Brussels	X	X				
Berlin	X	X	V/M	26	M	5
Hamburg	W.T.	4	M	1	W.T.	4
Munich	X	X	V/M	1-2		
Toronto	W.T.		M	0.15	VT/M	16
San Francisco	VT/M	3	M	0.15	VT/M	3
Chicago	X	X	M	1	M	
Boston	X	X	M	0.15-1	M	
N.Y. Path						
N.Y. CTA	W.T. (W.T.)	52 (18)*	M			

Legend: Frequency is expressed in weeks

V.T. = Vacuum train
VT/M = Vacuum rail mounted, manually operated
W/M = Water, manually applied
W.T. = Wash train
V/M = Vacuum equipment, manual operation
M = Manual pick up
* = Planned equipment
X = Not cleaned

Figure 3-9. TRAINWAY CLEANING

The dry system was selected for London because it maintained low humidity in the deep tunnels and reduced the exposure of electrical installation, e.g. cables and lights, to water.

The wash train, as developed by NY CTA appears much simpler in mechanical principle than the vacuum system and is probably lower in first cost and operation. However, for the reasons true in London, it may not have universal applicability.

Dust Generation

The major sources of dust are:

The train brake shoes – these are often composed of a variety of metallic elements. An analysis of two samples by Toronto indicate major proportions of iron (Fe) up to 50 percent, graphite 35 percent, and lead,

The wheels and rails during the movement of the train (and brakes on the wheels) – this is almost all elemental iron (Fe),

The rail grinding operation – a large proportion of the dust will be composed of the grinding medium, e.g. carborundum or brick dust depending upon the method used as well as the 1 mil or more iron removed from the rail head,

Cement dust from the concrete portions of the structure, and

The outside from which road and other dust enters the trainway from the ventilation structures and the stations.

Analysis of samples of dust from the trainway in London's tunnels indicates the major fraction to be 55 percent elemental iron and the rest to be iron oxide (21 percent), silicon (SiO_2 – 10 percent), and carbon (10 percent). The samples also contained 2 percent to 7 percent oil. At both Toronto and Chicago analysis of samples found the same materials as the

major fractions. The elemental iron particles are angular and magnetic and interlock as they are deposited (Tunnel Wash Trains) which makes removal difficult, especially when oil is present.

Effect

Dust has the following injurious effects: Reports on Investigation into Mechanical Cleaning of Tunnels):

> Its abrasive nature accelerates wear of mechanical equipment both fixed and in rolling stock. In Toronto, escalators to platform level require more frequent maintenance (than elsewhere) because of this,
>
> Its accumulation creates fire hazards that can short out train signal circuits relays and other electrical wayside equipment,
>
> Its presence on TV monitoring equipment and lights decreases their efficiency,
>
> Its accumulation on mortar joints of tile wall finishes, all ledges, and rough surfaces detracts from their appearance, and
>
> It can become both a visual problem and a health hazard.

Cleaning Equipment

Both the vacuum and wash systems of mechanical cleaning of trainways have been documented in detail by engineers of the London and NYCTA Systems, and only the more important features will be described here.

London. The system was designed after full scale tests in the circular tunnels were made with rail mounted vacuum equipment. The tests proved the equipment effective in removing accumulated dust from exposed cable banks and other items supported on the tunnel walls, as well as from the trainway invert. (The Paris system has for some time successfully used vacuum trains of similar principle for trackway cleaning.)

After the successful conclusion of the tests, the equipment shown in Figure 3-10 was designed and its manufacture was well advanced in December 1976 when the author visited the assembly shops.

The train has five units. The center one contains blowing and suction jets; on each end are two identical filter cars, which in turn are joined by two identical power and driving cars.

Figures 3-10 also indicates the principal details of the individual cars. The center car has adjustable high pressure blowing nozzles which are directed onto the trainway and the sides of the tunnel. The suction nozzles are ahead of and behind the blowers and also directed towards the trainway and the walls. Ducting from the suction nozzles leads through two settling chambers which collect debris and the heavier material. A 55 hp blowing fan is housed in this unit.

The filter cars contain filter bags arranged to operate in alternate banks. When one bank is filled, the suction is diverted to another bank and a vibration mechanism is activated to shake the dust from the full bank onto an underlying conveyor belt.

The power and driving cars each contain 140 hp suction fans connected by flexible ducting to the filter cars. The air is exhausted to the tunnels through louvers placed in the sides of the cars. Electric power is picked up from the 600 V dc train contactor rail.

The train only has sufficient capacity to clean one side of the tunnel wall or the track during one run. Cleaning the 133 miles of tunnel inverts and the walls for a foot or two above, up to the time of writing, has been undertaken manually at the rate of about 35 miles per year (i.e., the total system is cleaned in 4 years). Much of the dirt that accumulated in the tunnels over decades has consolidated and has not been removed

by the cleaning gangs, and in general none at all from the walls, supported cables, and other equipment. It is anticipated that the initial cleaning with the vacuum train will be much slower than succeeding runs, and will have to be followed with one manual operation for the removal of calcified and impacted dirt, grease, advertising paste, etc. In addition, enlarged tunnel sections, such as cross-overs and cross passages, will always require hand cleaning by extension suction hoses from the train.

On the basis of approximately 4-1/2 hours of nonrevenue service per night and 3 hours effective working time, the following cleaning schedules show the order in which the areas are cleaned and how much of each can be cleaned in an hour:

First cleaning completed in 12 months:

LH side of tunnel, 1/2 mph,

RH side of tunnel, 1/2 mph, and

Track invert, 1 mph.

Subsequent cleaning completed in 4 months:

LH sides of tunnel, 1-1/2 mph,

RH side of tunnel, 1-1/2 mph, and

Track invert, 4-1/2 mph.

The remaining 8 months would be used for several additional track invert cleanings.

The train staff will consist of three workers with two additional men required for discharging the train at the completion of each shift. Extra staff will be needed for track control during the operation of the train.

Auxiliary equipment includes fire control and explosion detection equipment.

New York. A prototype tunnel wash system was put in service to clean the 450 miles of tunnel in 1967. The system consisted of two trains, one to apply detergent, the other to rinse. Figure 3-10, "Prototype," shows the detergent train of six work (or power) cars, one tank, one pump, and one idler car. The rinse train has a similar mix of cars plus an extra tank car.

Both the detergent and rinse cars had nozzles arranged to direct the spray around the perimeter, including the roof but not directly on the track, of cut-and-cover and tunneled structures. Nozzles were also provided to clean under the nosing of the station platforms. All power was provided from the 600 V dc train contact rail through the six power cars; their design speed was 5 mph.

Revenue service is provided 24 hours a day, and the washing was done 5 nights a week between the hours of midnight and 6 a.m. when the scheduled time between the trains is longer. The detergent train sprayed 30 minutes ahead of the wash train. With two 8,000 gallon capacity tank cars, the wash car could operate for 30 minutes and clean an average of 2-1/2 miles of tunnel. Because of the logistics of filling the tanks from water hydrants located at the terminal points of the lines, only one run could be performed each night.

The high-velocity knife-like sprays of the rinse nozzles proved very effective in dislodging the dirt particles and flushing them into the roadbed and thence into the drainage system.

In addition to a driver, three men were required to operate each pump car.

Following the success of the prototype, a new system was designed, and these trains are shown also in Figure 3-10. New layouts of the detergent and wash water spray cars are shown in Figures 3-11 and 3-12. The primary features are:

A diesel electric locomotive provides traction for the trains,

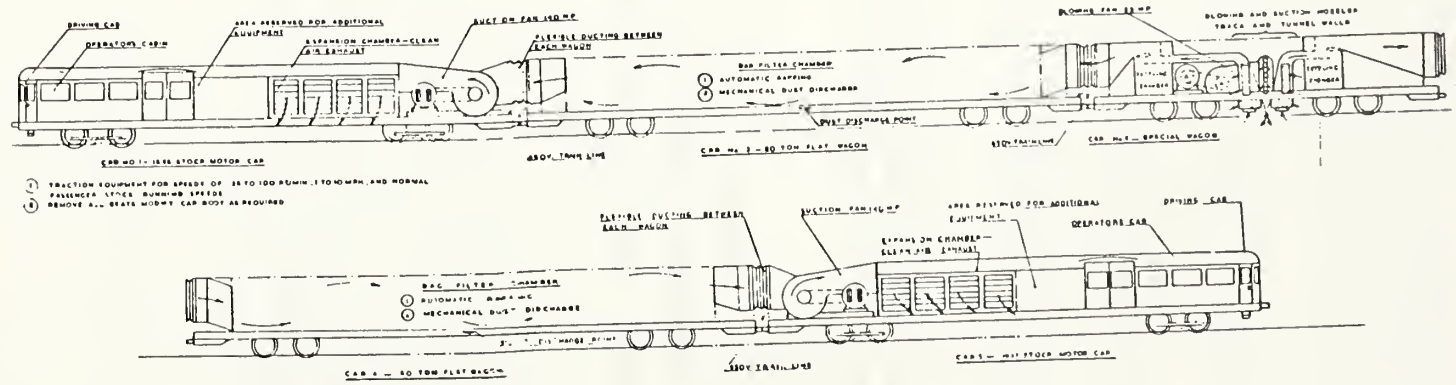
The detergent train is composed of three cars and a locomotive; the wash water train of four cars and a locomotive,

The detergent car pump is independently provided with a 90 kW diesel electric generator; the wash water car with one of 175 kW, and

The configuration of the spray jets for both detergent and water were slightly modified from the prototype as indicated in Figure 3-13; the trackway is also covered by the cleaning jets.

Two trains for each function were provided and this permits cleaning the 450 miles of tunnel on the schedule described above for the prototype in four months. The pump car staff was reduced from three to two.

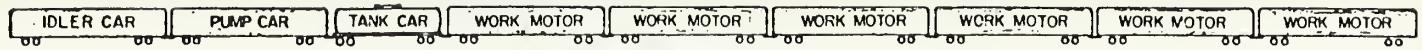
The present washing schedule as mentioned previously is constricted by the logistics of refilling the tank cars from hydrants at the terminal points of the lines. The possibility is being studied of establishing hydrants at convenient intermediate points along the lines to permit the trains to complete two cycles per night. If this can be done, the entire route could be washed in two months.


DRIVING CAB
OPERATORS CABIN
AREA RESERVED FOR ADDITIONAL EQUIPMENT
EXPANSION CHAMBER — CLEAN AIR EXHAUST
DUCT ON FAN 150 HP
FLEXIBLE DUCTING BETWEEN EACH WAGON
BAG FILTER CHAMBER
AUTOMATIC RAPPING
MECHANICAL DUST DISCHARGE
DUST DISCHARGE POINT
BLOWING AND SUCTION HOSES ON TRUCK AND TUNNEL WALLS
CAR No 1 — 1500 STOCK MOTOR CAR
CAR No 2 — 80 TON FLAT WAGON
CAR No 3 — SPECIAL WAGON
TRACTION EQUIPMENT FOR SPEEDS OF 25 TO 100 R.P.M. (50 TO 400 H.P.) AND NORMAL PASSENGER STOCK RUNNING SPEEDS
REMOVE ALL SEATS NORMALLY CAR BODY AS REQUIRED
FLEXIBLE DUCTING BETWEEN EACH WAGON
SUCTION FAN 150 H.P.
AREA RESERVED FOR ADDITIONAL EQUIPMENT
DRIVING CAB
OPERATORS CAB
EXPANSION CHAMBER — CLEAN AIR EXHAUST
BAG FILTER CHAMBER
AUTOMATIC RAPPING
MECHANICAL DUST DISCHARGE
CAR 4 — 80 TON FLAT WAGON
CAR 5 — 1500 STOCK MOTOR CAR

PROPOSED ARRANGEMENT OF TUNNEL CLEANING TRAIN

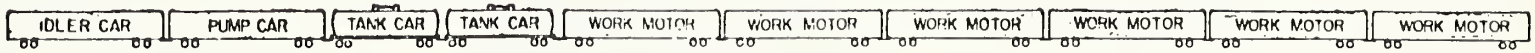
DIAGRAM E

Figure 3-10



DETERGENT UNIT

PROTOTYPE (1 UNIT)



RINSE UNIT

PROTOTYPE (1 UNIT)

DETERGENT UNIT

NEW (2 UNITS)

RINSE UNIT

NEW (2 UNITS)

WASH TRAINS — TRAIN CONSIST

Figure 3-11

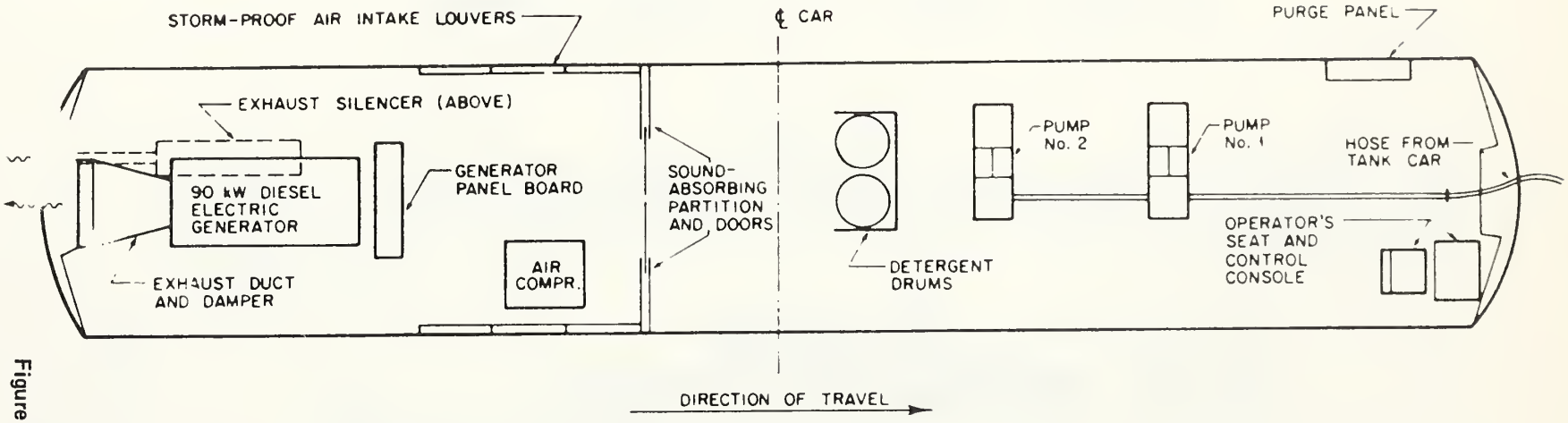


Figure 3-12

NEW DETERGENT PUMP-SPRAY CAR

CAR Nos. 30631 AND 30632

EQUIPMENT LAYOUT

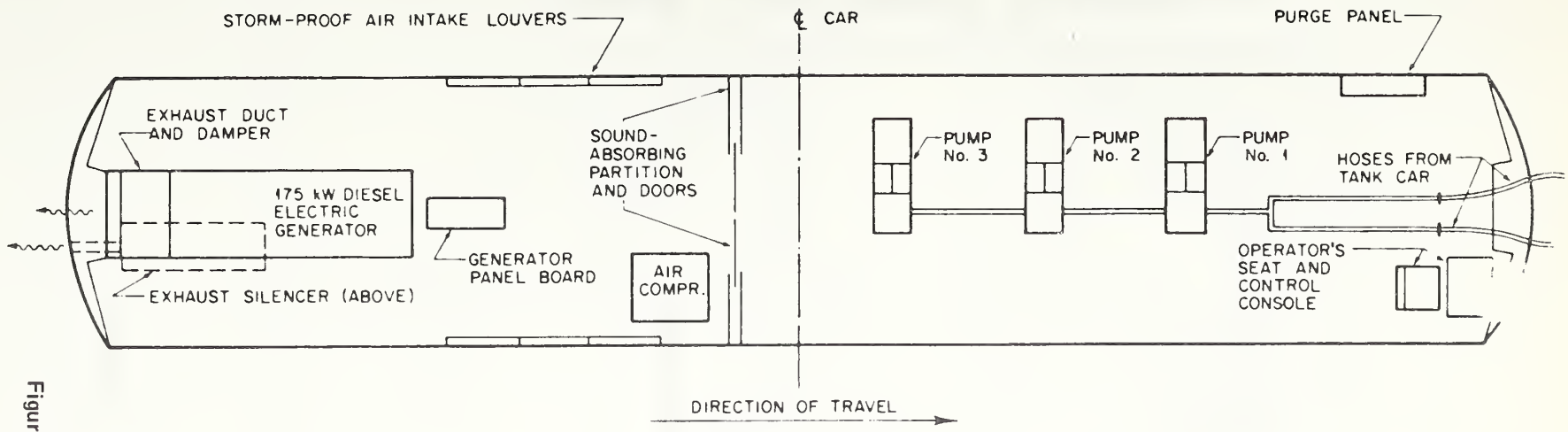


Figure 3-13

NEW RINSE PUMP-SPRAY CAR

CAR Nos. 30630 AND 30633

EQUIPMENT LAYOUT

NEW DETERGENT AND RINSE UNITS
PUMP CAR SPRAY PATTERNS
COMPOSITE OUTLINE
STATIONS — TUNNELS

Figure 3-14

4 DEFICIENCIES IN STRUCTURES, FIXED EQUIPMENT, AND STATION LAYOUT

This section identifies deficiencies in the design, details, and materials of the subway structures and their constituent items. Unsatisfactory aspects of station space allocation and layout are also discussed. The underlying causes of the deficiencies are discussed, and their deleterious effects upon the principal maintainable items are examined in detail.

The identification of the deficiencies and their impacts required both an analysis of the technical data presented in Section 3 and the record of discussions with engineers at the cooperating properties. In addition, a number of specialists were consulted about such subjects as concrete technology, waterproofing materials, cathodic protection, mechanical and electrical equipment, and engineering economics.

STRUCTURES

The transit property study identified two principal systems of underground construction: cut-and-cover and tunnel. Each of these comprises several structural types as summarized in Table 4-1.

These structures were surveyed to identify characteristic deficiencies which are categorized in the following paragraphs.

Table 4-1

CHARACTERISTICS OF UNDERGROUND CONSTRUCTION SYSTEMS

Construction System	Structure Type	Description or Construction Method
Cut-and-cover	Rigid frame	Monolithic reinforced concrete slabs or slabs, beams, and columns
	Articulated	Slurry concrete or secant pile exterior walls, remainder of structure cast-in-place or precast concrete
	Jack arch	Steel beams and interior (and sometimes exterior) columns with cast-in-place concrete roof floor and wall slabs
Tunnel	Metallic or concrete segments	Segments either bolted or articulated
	Cast-in-place concrete (for soft ground conditions)	Initial temporary support of ribs and lagging or segments
	Cast-in-place concrete (for rock conditions)	Generally with temporary support comprising steel ribs, ribs and lagging, or rock bolts
	Shotcrete (for rock conditions)	Often supplementary to rock bolt or steel rib temporary support

Cracks and Joints

Unsatisfactory performance of the structure was frequently evident from water seepage through concrete, cracks, and expansion and construction joints in the cast-in-place concrete structures and through the interfaces of segments in tunnels with these linings. Generally, the cracks were parallel to the span of the structures (i.e., transverse to the length) and were generated by shrinkage of the concrete during construction. In themselves, these cracks did not impair the load-bearing ability of the structures, but they were undesirable because of water seepage and its

long-term multiple effects on many of the maintainable items, including the structure itself. The cracks could be attributed to all of the following:

The concrete mix (or composition),

Engineering design,

Construction specifications, and

Overstress from differential ground settlement.

Concrete Spalling

Spalling of concrete was experienced in three types of structures:

Cast-in-place structures in variable ground generally experienced spalling at keyed expansion or construction joints because differential ground movements produced excessive shearing forces across the joints,

Precast-concrete-lined tunnels tended to spall along the segment edges and at the corners. Causes included mechanical damage during transportation and erection of the segments in the tunnel, damage from the shoving jack in shield-driven tunnels, and faulty segment interface design details causing excessive point bearing pressures, and

In shotcrete-lined tunnels spalling developed generally in localized areas because of inadequate bonding to the rock or, occasionally, because of instability of the rock itself.

Defective Concrete

Defective concrete was detected in a few of the structures inspected, generally in the form of honeycombed areas. These were often at expansion and construction joints but sometimes in random areas of the wall and roof members. Seepage and spalling generally resulted from this condition. Honeycombing was usually attributed to inadequate compaction or placing methods during construction.

Waterproofing Systems

Different water proofing methods were used for cut-and-cover structures, for tunnels with cast-in-place-linings, and for tunnels with segmented linings.

Cut-and-Cover Structures. Water proofing membranes were applied to the outside of the structure and, generally, protective barriers were installed on the walls and roofs before backfilling the excavation. Failures of the waterproofing, as evidenced by appreciable leakage through the structures, appeared to stem from the following causes:

> Where waterproof membranes did not extend all around the structures, the sealing of the discontinuous edges was defective or the space between the expansion joint and the water barrier was not sealed,
>
> Joint laps on the membranes failed, or the membrane was punctured during installation. In both cases, workmanship was often at fault, but sometimes the design detail was deficient, and
>
> Breakdown of the membrane material from length of service combined with adverse chemical environment.

Tunnels: Cast-in-Place Linings. Transit properties in West Germany and Stockholm had tunnels constructed with a continuous bitumastic membrane sandwiched between the inside surface of a primary lining and a secondary inner concrete lining. Virtually no leakage was reported in these tunnels. Presumably, if the membrane was properly installed and care taken not to damage it during the placing of the secondary lining, as apparently was achieved in both properties, satisfactory performance could be expected.

Tunnels: Cast-in-Place Linings. Transit properties in West Germany and Stockholm had tunnels constructed with a continuous bitumastic membrane sandwiched between the inside surface of a primary lining and a secondary inner concrete lining. Virtually no leakage was reported in these tunnels. Presumably, if the membrane was properly installed and care taken not to damage it during the placing of the secondary lining, as apparently was achieved in both properties, satisfactory performance could be expected.

The San Francisco property had experienced problems with stress/corrosion fatigue of the high tension segment bolts in steel lined tunnels in salt water.

In the few instances where concrete segments had been employed in wet ground, leakage through the joints appeared to be more or less a continuing problem because of the difficulty of maintaining the caulking tight in the relatively soft concrete groove and the more lively (than with steel) segment interfaces. Leakage did not seem to occur through the segments themselves.

Results of Structural Deficiencies

Continual seepage of water into the structure through cracks or from failures of waterproofing systems has insidious effects on the structure itself as well as on several components and items installed within the underground system. These effects are summarized in the following paragraphs.

Corrosion. The principal items affected by corrosion are:

Track rails and fastenings,

Train and track control equipment,

Metallic items installed in the trainway such as "unistruts," hangers, conduits, and light fixtures,

Metallic tunnel liners and structural steel incorporated with the concrete structures,

Reinforcing steel in the concrete structures,

Miscellaneous metal in the appurtenant structures, and

Electrical control equipment within the appurtenant structures; also mechanical equipment to some degree.

Concrete Deterioration. Water continually flowing through cracks frequently contained chemicals that leached free lime and other substances from the cement causing a gradual breakdown in the concrete.

Effect on Drainage and Pumping Systems. All water entering the subway must be channeled into gutters, catch basins, and piping to the pump sumps and then pumped out. The cost of maintaining all these items

depends on the quantity of water, its chemistry, the solids content, and the amount of dirt and debris in the trackway and other areas that contribute to clogging of the drainage system. The more water entering the system, the greater will be the compounding of these items and subsequent costs of monitoring the system.

Stray Electrical Currents. Water and dampness are the principal vehicles by which stray currents from the running rails — current return — pass through the structure into the surrounding ground. Under certain situations, these currents have the following effects:

Corrode metallic utility pipes,

Interfere with the performance of external cathodic protection systems,

Corrode metallic components in external structures, e.g., structural and reinforcement steel in concrete structures, piles, retaining walls, and

Corrode similar metallic components in the subway structures.

Effects on Architectural Finishes in Stations. Water seepage results in the following:

Discoloration of surfaces and deterioration of finish materials,

Corrosion of metallic hangers, fixings, light fixtures, and other wall and ceiling components, and

Hazardous conditions for walking on stairs and floors.

Structural cracking and joint displacement had a pronounced effect on architectural finishes that were applied directly to the structural members. In such situations, the structural cracks were usually propagated through the tile or terrazzo finish not only affecting appearance, but, in some cases, loosening wall, ceiling, and floor tiles sufficiently to create potential danger to the occupants.

In general, spalling and cracking of concrete structures did not affect the performance of the items within the trackway or the train. In one

instance, New York NYCTA, severe vertical displacements in a length of cut-and-cover trackway (caused by very unstable ground), necessitated relaying the track.

Distortions within tunnels never appeared to be sufficient to affect the train structure clearances. The falling of concrete fragments from spalling of the shotcrete tunnel linings, e.g., Stockholm, did not appear to be a matter of serious concern in respect to train safety; however, the condition generated maintenance costs.

DRAINAGE AND VENTILATION FACILITIES

This subsection reviews the facilities provided for the drainage and ventilation of the subway and identifies what may be considered undesirable features in these facilities in respect to maintenance.

Drainage Facilities

The following are the findings on collection systems:

> Gratings oriented with bars across, rather than parallel to, water flow were easily clogged by paper and other trash and required frequent cleaning,
>
> Where drainage falls were restricted, inadequate sizing of catch basins resulted in frequent clogging and required cleaning of the basins and piping,
>
> Details of catch basins, clean-outs, and piping were unsatisfactory in respect to ease of cleaning, and
>
> Piping was not designed to avoid fracture in areas of structure movement.

In addition to the above, in some of the older installations the metallic piping had more or less completely corroded, considerably reducing the effective drainage area and the efficiency of the system.

Pumping stations were found to have these problems:

Difficult accesses for pump maintenance; e.g., accesses across conductor rail in trackway only,

Inadequate head room to pull pump for maintenance; poor access to pump impellers (and motor when submerged),

Poor provisions for sump cleaning; e.g., no secondary dewatering sump provided, poor accesses to the sump, and

Inadequate facilities for handling and removing sludge and debris; solids entering the drainage system contain grease, oil, and metallic dust which increase the difficulty of debris removal.

Ventilation facilities frequently presented the following problems:

Shaft surface terminations in street or sidewalk where they collect dust and debris and are vulnerable to flooding, oil and gas spills, and vehicle fumes,

Shaft surface terminations in street making access to trackway from surface difficult, and

Inadequate provisions for shaft cleaning and debris removal.

In some instances (San Francisco) where shafts vented to street or sidewalk, accumulated debris had to be removed monthly. In general, the air passing through ventilation shafts carries a certain amount of oil and metallic dust which compound the difficulty of the shaft cleaning process.

MECHANICAL EQUIPMENT

Pumps

In all properties surveyed, the pumps installed appeared to provide satisfactory reliability. Many pumps had been in service with no extensive repair for several decades. There was criticism at some of the newer properties of oversizing the pump capacities which caused frequent stopping and starting resulting in increased power consumption

as well as the wear and tear that shortens pumps life. Maintenance efforts could probably be reduced by the installation of automatic greasing devices or sealed bearings, as is done in many newer installations.

Fans

The ventilation fans installed at properties were generally satisfactory. However, only in London and Paris (to some extent) were fans used continuously; in six properties fans were used seasonally or in emergencies only; and five had no fans installed at the time of the investigation. The history of fan performance, therefore, was limited and no deficiencies were identified.

Escalators

Maintenance personnel interviewd at all properties were very conscious of defects in their escalator systems, and many were engaged in ongoing programs to correct undesirable features. The following summarizes the defects encountered:

Mandatory public bidding procedures (generally requiring acceptance of the lowest bid) often resulted in installation of escalators from several different manufacturers. This situation reduces maintenance efficiency and increases the complexity of maintaining a spare parts inventory,

The major escalator market is created by commercial buildings and is for lighter duty escalators than those desirable for subway properties. Heavy duty equipment should be more economic for the rigorous service imposed at a transit station, but such is becoming nonstandard equipment and, therefore, expensive to purchase,

Commercial building escalators are more costly to clean and maintain than are heavy duty ones,

No speed control capability during low traffic times,

Inadequate lighting coupled with glare generating treads,

No safety marking of treads, and

No monitoring of safety buttons with consequent frequent misuse.

Fault monitoring not provided at station attendants booth to reduce cost and time of unscheduled maintenance,

Handrail material unsatisfactory,

No provision in housing under escalator for easy accessability and maintenance, and

No automatic oiling and greasing systems.

Elevators

Both in this country and abroad, elevators installed by transit properties appeared to be uniformly reliable. When malfunctions did occur, they generally related to the door-moving mechanism, as did passenger accidents.

Typical comments by transit maintenance engineers about elevator installations are summarized as follows:

Elevators were not designed to accommodate accident stretchers or station maintenance equipment or did not serve all levels of the station complex,

Elevator interiors, particularly in those operated by the passenger, were not designed to minimize vandalism, and

Door operating mechanisms too complex; they should be as simple and robust as possible.

Lights

A summary of comment and observation on the lighting systems follows:

All lights should have waterproof, corrosion resistant fixtures,

Lights should be placed beyond easy reach of the public,

The general intensity of lighting should be increased in areas of high traffic density,

Covers should be eliminated to maximize lighting efficiency,

Planned cleaning programs are required, and

Periodic batch replacements of lamps generally appears to be more economic than spot replacement.

ARCHITECTURAL FINISHES

The following paragraphs summarize comments of the transit maintenance engineers (and architects) as well as observations of the author on unsatisfactory architectural finish material and use.

Floors

The following problems relate to both construction materials and methods.

Monolithic terrazzo in areas of heavy wear is unsatisfactory because of the time and equipment required for repair and replacement,

To be satisfactory, the design of monolithic finishes, either incorporated with the base concrete or separately, must make provisions to: minimize shrinkage and thermal cracking of the structural slab; reflect all structural construction and expansion joints in the floor topping; effectively bond-separate the finish topping from the structural unit,

Tile cracking was observed in many instances, and where tiles had been bond-separated from the structural slab, these defects could be attributed to excessive thermal movement combined with expansion joints in the tile mat improperly designed or located,

Flooring of very light or dark colors was generally judged unsatisfactory because of staining or showing up dirt more readily than a material of intermediate or variagated color or pattern,

Rough textured materials — such as granite, slate, and to a lesser extent brick — are poor choices because they are hard to clean, and

If not struck flush with the floor surface, mortar joints can make cleaning difficult.

Stairs

Stairs were surveyed with considerations for tread material, ease of replacement, and lighting.

Any form of terrazzo appears unsuitable for stair treads because it wears poorly and is vulnerable to mechanical damage,

The tread nosing in nearly all materials (except perhaps granite) will suffer damage from chipping and wear to the extent of becoming dangerous, unless it is especially protected with metal or readily replaceable tile or other material,

In some of the newer properties the stair treads had not been originally designed for periodic replacement; this is considered a defect, and

In some instances stair lighting and tread marking were so inadequate as to create a potentially dangerous situation.

Walls

Wall systems investigated in many cases revealed problems with structure inspection, corrosion, vandalism, construction details, and appearance.

False wall systems that do not provide ready access for inspection of the structure behind are deemed undesirable,

False wall metallic ties to the structure and other metallic components may suffer from corrosion unless they are of stainless steel, adequately ventilated, or the structure properly waterproofed,

Wall finish material accessible by the public is unsatisfactory unless it is vandal resistant. Characteristics required include hard with moderate-to-high glaze finish and nonabsorbent hard mortar joint pointing. Rough surfaces pick up dirt and are particularly difficult to remove defacements from,

When applied directly to the structure, large tile units (vitrolite, terra-cotta, etc.) are more subject to cracking from structure movements than are small units,

If mortar is too strong, it is likely to propagate structural cracks and movements through a hard tile finish; it should be plastic and only sufficiently strong to hold the tile in place,

Highly polished stainless steel and other metals in contact with the public require frequent cleaning to maintain a good appearance; surfaces should be mat or brushed, and

Glass in contact with the public may be a high cost maintenance item because of the need for both frequent cleaning and replacement.

Doors

Doors are potentially heavy maintenance items in two locations: at public entrances to the stations and in the trackway. In the former location, frequent maintenance was generally required if the following were not incorporated in the door design.

Heavy construction of door and frame; heavy duty hinges and closures, the latter with ready access for maintenance (i.e. not concealed), and

Heavy shatter-proof glass, some properties limit this to the upper portion of the door only.

Trackway doors to pump rooms, emergency exits, etc., were often damaged by the oscillating high pressure air waves generated during the passage of the train. Such conditions require extra heavy doors, frames, and, particularly, hardware. In addition, the corrosive conditions generally prevailing in these locations require heavy duty corrosion protection of all metallic parts.

Ceilings

Similarly to the walls, ceiling finishes were either applied directly to the soffit of the structure or on a framework supported from the soffit, i.e. false ceiling. A summary of unsatisfactory materials and details observed or recorded in discussion is presented below.

The following observations were made of finishes applied directly to soffits:

Ceramic tiles are satisfactory providing the requirements discussed for walls as to composition, color, and mortar bedding and joints are observed,

Seepage or dampness through the structure was the chief cause of damage to paint; structural cracking of concrete or masonry was generally reflected through the paint film and detracted from its appearance; repainting is usually required every 7 years, and

When sealed and finished with paint, acoustic plaster presents the same problems as occur with paint applied directly to the concrete (or masonry). When left unsealed and painted, this material was very prone to attract moisture and dirt, difficult to clean, and subject to mechanical damage.

Hung or false ceilings comprise two general systems; solid and open grid (e.g. egg crate). The following unsatisfactory details were identified:

Materials or their configurations made cleaning difficult. Such materials included perforated panels in asbestos or metal, acoustic spray or tiles, and composite units such as inverted plastic or metal channels backed with acoustic panels,

Solid ceilings were not designed to permit periodic inspection of structure above. Most engineers with whom this was discussed opted for crawlways with a minimum space of 24 inches; a few believed removable ceiling panels were satisfactory, and

Height of ceiling was too low (less than 9 feet), allowing damage to the material and lights by the public.

Finish Material Recommendations

Many engineers interviewed stated that most of the finish materials used are difficult to match after a period of time when spot replacement is required. Particular problems were experienced with mono colors in

tiles and terra-cotta brick. A consensus recommended that, where possible, varigated colors should be selected and materials for replacement should be stockpiled at the stations where they would be used.

STATION LAYOUT AND DETAIL

Many of the engineers interviewed felt that, to optimize the cost and effectiveness of the maintenance process, the following criteria should be adopted for further installations. The rationale for some of the criteria is discussed further in Section 5.

The following provisions and procedures were recommended:

Provide adequate space in proper locations for storage of cleaning and other maintenance equipment, material supplies, and garbage,

Reduce, as far as possible, the diversity of architectural and other materials and components and sensibly standardize them throughout the system,

Protect finishes sensitive to vandalism by providing barriers between them and the public; provide minimum ceiling heights of 9 feet,

Design all floor mounted components for ease of cleaning; i.e., where possible, avoid dead spaces and pockets and provide clearances that permit the maximum use of cleaning and washing equipment,

Design elevators to move maintenance equipment, supplies, and garbage and to serve all floor levels,

Plan station layouts for easy surveillance by the attendants,

Provide for drainage in floors for cleaning water, and

Provide adequate electrical outlets for cleaning and other maintenance equipment.

5 ENGINEERING DESIGN PRACTICES TO MINIMIZE MAINTENANCE OF STRUCTURES AND ARCHITECTURAL FINISHES

The service life of an underground transit structure generally greatly exceeds that of most other publicly used structures. Many transit systems in this country and abroad operate underground structures that have been in service since the turn of the century (some were constructed 70 years ago) and will probably remain in service for many decades.

The service routes of transit systems do not "wear out." Within a metropolitan complex, intensive development generally takes place around the transit stations which, once located, become permanent anchors for many of the activities within the complex.

Replacing an underground transit structure in a downtown area is exorbitantly expensive and predictably will be even more so in the future. Repairing underground structures from the outside below busy streets, even where practical, is time consuming and costly. Once the trains are in service, repairs and routine maintenance from within the trainway structures are usually difficult and expensive. Therefore, the initial durability built into the structure and its details assumes considerable importance in the maintenance economics of a transit system.

Architectural finishes and mechanical and electrical fixed equipment have shorter useful lives than the structures, and periodic replacements can be anticipated and should be planned for. These periods range from as little as 5 years for stair treads and painted surfaces to 50 years for tiled walls and ceilings, escalators, etc.

With the objective of increasing the durability of the elements and components of future installed underground transit structures and to overcome the deficiencies discussed in Section 4, the appropriate design philosophy and construction procedures for new installations are discussed in this section.

SERVICE CONDITIONS

Most of the underground structures of existing U.S. and foreign transit properties and those likely to be constructed in the next decade or so are or will be located in grounds with high water tables. The degree of water pressure on the structures varies from intermittent (from precipitation on structures constructed above the permanent groundwater table) to substantial continuous pressures on deep structures beneath a high water table.

Underground structures are generally subject to considerable strains and stresses from ground movements occurring after construction. Some of these movements are inherent to the type of ground encountered:

Sensitive clays and silts undergo volume changes when disturbed by the construction operations,

Groundwater table changes during or after construction may cause ground settlement,

Tunneling operations cause rocks to undergo stress changes that may continue sometime thereafter,

Variable ground may cause differential settlements,

Adjacent construction operations such as deep excavation, pile driving, ground surcharging, etc., may cause ground movements, and

Seismic shock may strain the structure beyond its elastic limit and create permanent ground displacement.

DESIGN CRITERIA

To assure maximum durability in the structural systems under investigation (and as listed in Section 3), design criteria should be formulated with consideration of the following factors:

Loading on a structure in reference to the geology of the terrain through which it is constructed,

The degree of external water pressure and the chemical composition of that water,

Durability of reinforced concrete including control of cracking, composition, placing, and curing,

Waterproofing membrane systems and water barriers, and

Corrosion protection systems.

These factors are related to the cracking of concrete structures, the principal cause of their long term deterioration. Conditions and causes of concrete cracking are discussed in the following paragraphs.

Loading and Geology

The soil or overburden pressures assumed in the design of an underground structure have an important bearing on the magnitude of structural cracking. Rigid frame reinforced concrete structures and, to some extent, cast-in-place tunnels are more vulnerable to such cracks, particularly on the earth faces, than are articulated structures and segmented lined tunnels.

Cracking occurs on the tension side of a structural member when the strain in the reinforcing bars, or structural steel, exceeds the corresponding strain capacity in the surrounding concrete. As strain is proportional to stress, concrete cracking may theoretically occur when the stress in the steel reaches 4,000 psi. The cracking is increased by the normal shrinkage of the concrete as it hardens, and also in some instances by plastic flow which occurs when concrete is under stress for long periods of time.

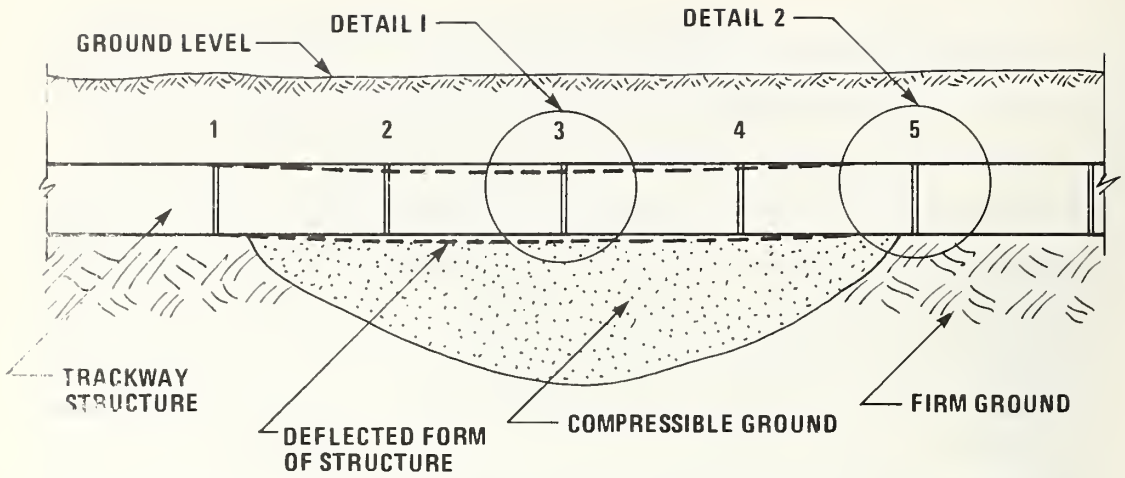
Vertical loading design criteria for cut-and-cover structures normally reduce the surface live load as the depth of ground cover above the structure increases. For example, the required live load may be 600 psf for 6 feet of cover, or approximately 40 percent of the total load. For 20 feet or more cover, the required live load may be zero. In the latter instance when back filling of the structure has been completed, the tension stress in the steel reaches and remains permanently at its working stress of perhaps 20,000 psi for intermediate grade and 30,000 psi for high grade steel. Here the cracking may become appreciable, is not structurally dangerous, and is acceptable on the air face of the structure; but on the ground face, water seeping into the cracks may cause steel corrosion and eventual deterioration of the structure. In these cases, criteria for the design of structures with high ground covers and in wet conditions should modify the allowable steel stresses to reduce the cracking incidence. In addition, the engineering specifications should be formulated to achieve low-shrink concrete.

Other forms of structural cracking can occur from differential soil movements (or pressure) both across the transverse and along the longitudinal directions of the structures. A stiff rigid structure is more vulnerable to straining and cracking than a flexible one. In unstable grounds, structural distress from transverse ground movements will occur when the displacements become greater than the structure's flexual capacity

to absorb them. In a rigid frame structure, all the joints (or lines of intersection of the various component members) in the structure will suffer strains as differential transverse forces are applied, and the component members themselves will receive transverse forces (or shears) across them. The extent of cracks occurring in the structure members will depend, of course, on the degree of movement impressed on the structure by the soils. A tunneled structure will be distorted by ground displacements in a similar manner, and a cast-in-place rigid (circumferentially) lining will be more subject to cracking than a segmented one that is generally more flexible – see DOT-TSC-OST-77-7, Systems Study of Precast Concrete Tunnel Liners. To minimize structural distress under such geological conditions, maximum ductility (or flexibility if structurally appropriate) must be a design requirement. Particular attention to attain this should be paid to the corners of cut-and-cover structures.

Differential ground movements or settlements along the longitudinal axis of the structure will bend it as a beam. In a longitudinally continuous structure that must follow the movements of the soil, strain will occur either in the top or bottom structure elements according to whether the soil movements produce "sagging" or "hogging" in the structure. The degree of cracking depends on the magnitude of differential movements relative to the beam stiffness of the structure. In many situations it is practicable to provide beam flexibility by using articulated joints in the structure at the interfaces of soils of variable stiffness to permit sagging or hogging of the structures. The joints are designed to permit vertical (and sometimes horizontal) rotation, but not shear, displacement. A typical arrangement and details of such joints are indicated in Figure 5-1.

The figure indicates a structure in generally firm ground extending over a compressible pocket. To permit the structure to assume the deflected form indicated in dotted line without overstressing and cracking, articulated joints are provided every 60 feet or so. These are shown for two actions. Detail 1 shows a joint near the center of a soft ground area at



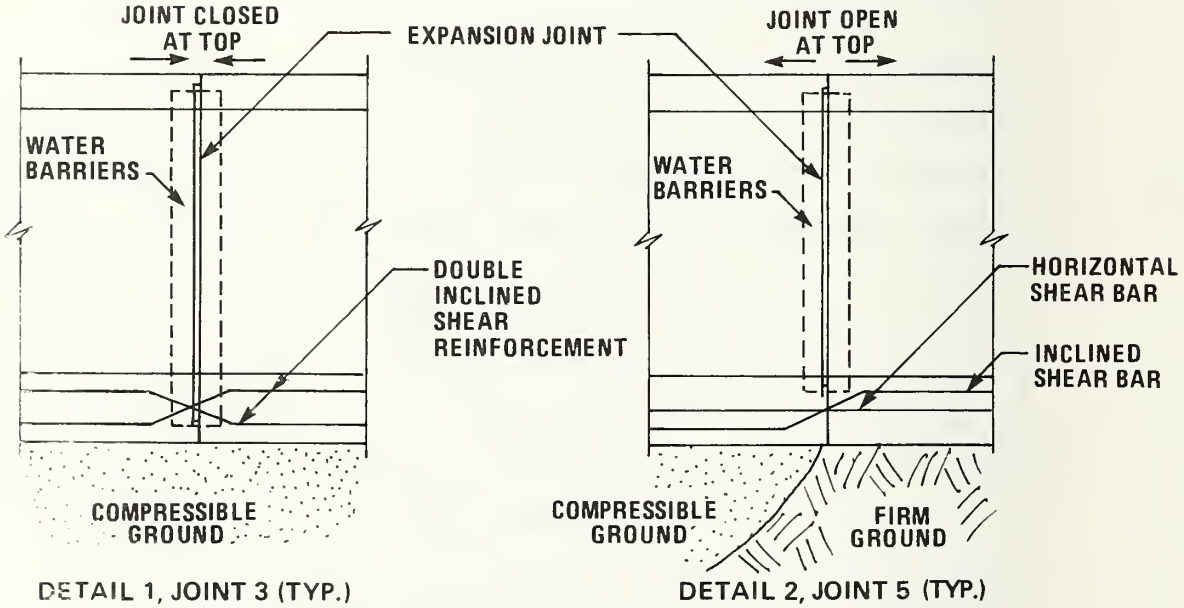


Figure 5-1. TRACK STRUCTURE DEFLECTION DUE TO COMPRESSIBLE GROUND

point of maximum deflection; this joint will close at the top. Theoretically, at this section there will be little vertical shear across the joint, but in practice some may occur on one side or another; hence the arrangement of the diagonal bars shown. In Detail 2 the joint will open at the top and the vertical shear, which must be accommodated in the bottom slab, is downwards to the left of the joint. In each detail concrete shear keys should be used, particularly in the invert and wall slabs, to assist prevention of horizontal and vertical displacements. Similar conditions may be imposed on structures in mixed grounds of rock and soft ground where the structures may hang up over rock outcrops.

The interfaces of structures of variable cross section, plan areas, and/or rigidity are particularly vulnerable to cracking and spalling damage from even slight ground movements. Examples of these include junctions between: entrance ways from the surface to the main station structure; trackway to station structures; ventilation, pump, and other appurtenant structures to trackway (and station) structures. Alternative structural details at the junctions appear to be designing the joints as strong (and also ductile) as possible, articulating the joints to provide for shear forces only, and providing structural separation. The latter details in wet ground conditions require careful consideration of preventing, or dealing with, water seepage. In seismic prone areas in ground of variable qualities, additional precautions must be taken in providing articulation for both horizontal and vertical movement.

Water Pressure and Composition

The height of the groundwater table above the top of the finished structures and the resulting pressures on it are major determinants of many of the design details (as well as construction methods) of the structure.

Even under a few feet of water pressure, structures will admit water either by seepage or dampness through the concrete itself unless special

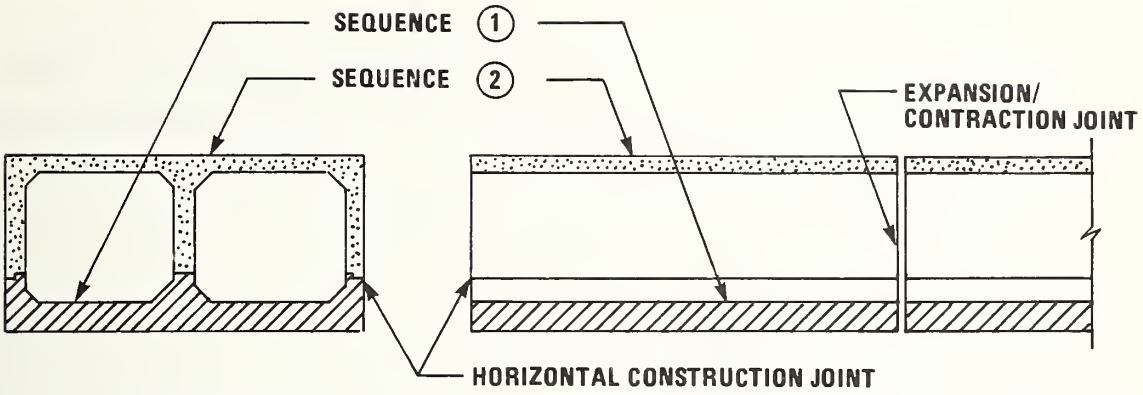
care is taken with the design of the concrete mix and its placing to minimize cracks and porosity. The design and construction of structural joints are equally important. As the water pressure increases, the difficulty of attaining satisfactorily watertight structures increases unless completely encapsulating membrane waterproofing is used.

The chemistry of the water is important because of the effect of seepage on the performance and longevity of the structures. Some dissolved alkalis (and solids) will, after a period, solidify in concrete cracks and prevent seepage while others will attack and destroy the cement in the concrete. Acids are generally deleterious to both concrete and steel. Both alkalis and acids conduct electric currents, and in groundwater they become agents for generating electrolysis in reinforcing and other steel and will eventually cause the breakdown of the structures.

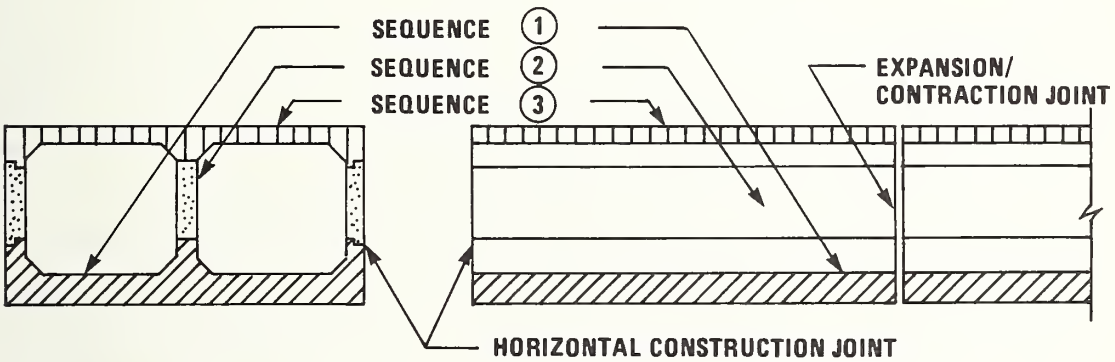
Durable Reinforced Concrete

Minimizing shrinkage and thermal cracking is essential for durability. In addition, the concrete must be designed for high density and strength and resistance against chemical attack. As newly placed concrete hardens, shrinking occurs as a result of both the chemical reaction in the cement when it is hydrated with water and the heat generated in the chemical action. When it hardens, it is at a higher temperature than it will be during the structure's lifetime, and the resulting temperature drop produces additional shrinkage in the concrete mass.

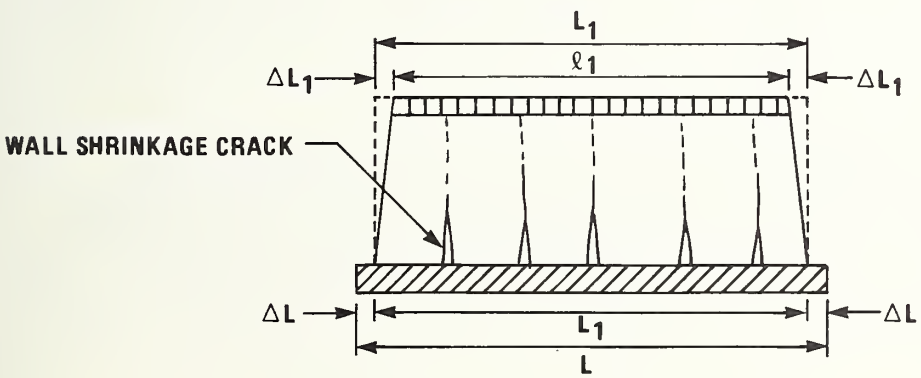
Providing the concrete is not restrained to prevent shrinkage movements (or contraction) cracking will not occur. However in the construction of cut-and-cover underground structures, restraint of shrinkage movement is exercised on some of the structure elements in the longitudinal direction; this arises principally from the sequence of construction. Two typical placing sequences of the concrete for underground box construction are indicated in Figure 5-2. In Detail A, the bottom slab, or invert, of a



DETAIL A
TWO PLACING SEQUENCES



DETAIL B
THREE PLACING SEQUENCES



LONGITUDINAL SECTION
DETAIL C
SHRINKAGE CRACK PATTERN

Figure 5-2. CONCRETE CONSTRUCTION CRACKING MECHANISM

trackway structure is placed first and the walls and roof are placed in one at a later stage (maybe 10 days later). Detail B indicates an alternative three-sequence placing: first the floor, next the walls, and lastly the roof.

In either case the preceding pour will have the same effect in restraining shrinkage and consequently generating cracks in the succeeding ones for the following reason. For an average construction unit length of up to 75 feet, the minimum normal area of longitudinal reinforcement provided in the invert slab is adequate to overcome the friction forces between the underside of the invert and the subgrade. Under the action of the concrete shrinkage forces (as the concrete hardens) and by the time the walls are placed, the slab will have shortened slightly, as indicated in Detail C by $2\Delta L$. The horizontal construction joint between wall and invert normally contains a considerable amount of vertical reinforcement and this, together with the roughness of the already hardened invert concrete, firmly anchors the concrete in the wall pour to the invert. The resistance of the invert will far exceed the shrinkage forces in the wall concrete which, as it shrinks, will develop vertical cracks greatest in width at the invert and diminishing at the top of the wall (or may not even extend to it, particularly when the roof and walls are placed together as in Detail A). If these two are placed separately, the same situation of shrinkage restraint by the walls on the top slab will exist as between wall and invert. In this case transverse shrinkage cracks will be propagated transversely across the roof slab.

The degree of chemical shrinkage in concrete depends largely on the water/cement (W/C) ratio of the mix, the cement type, and the grading of the aggregates. Generally, shrinkage decreases and strength increases as the W/C decreases; consequently, the concrete design should be based on this factor.

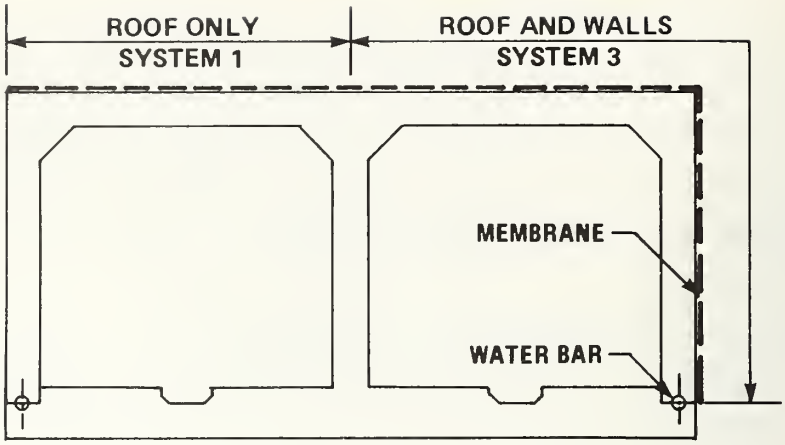
Reduction of the temperature of concrete during hydration may be achieved by attention to several factors in the design and placing of the

mix. These include selection of the cement and the use of admixtures; cooling the concrete (e.g., by adding ice to the mixing water) to allow placing at a low temperature, particularly in hot weather; spraying cooling water on the forms after the concrete has been placed; and curing the concrete with water sprays.

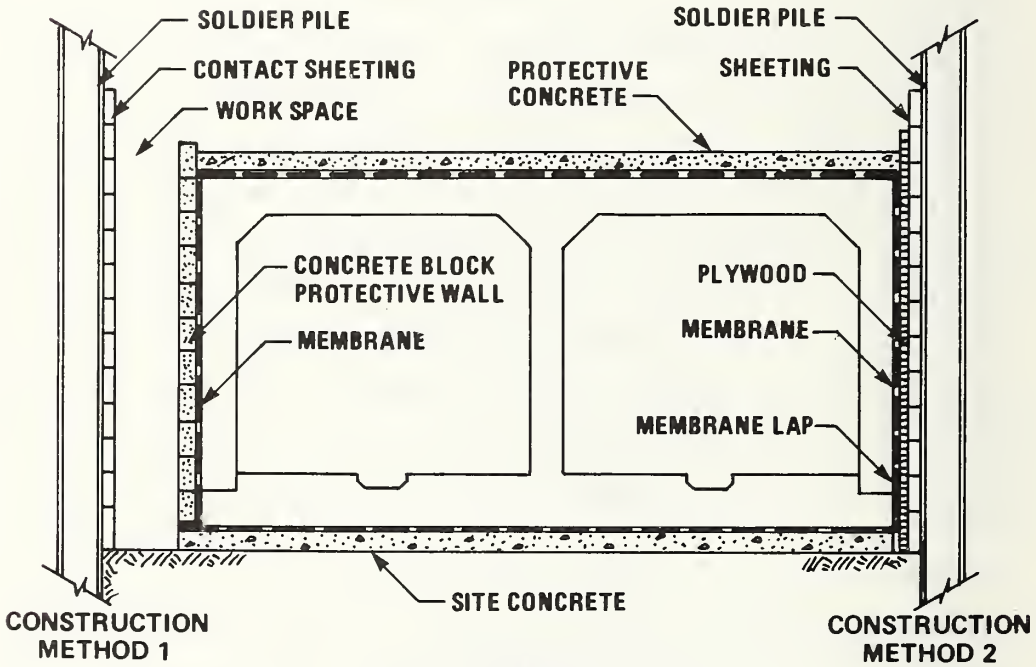
The selection of materials for resistance against chemical attack and for strength as well as the most pertinent factors affecting chemical and thermal shrinkage in concrete are discussed in detail in Appendix D.

Waterproofing Membranes

Water seepage over the years has insidious effects on underground structures and the train support systems. In some situations, sufficiently high water tables and chemically aggressive water may warrant the prevention of water seepage and dampness altogether. Several overseas properties recognize this by using continuous membranes to completely encapsulate both cut-and-cover and tunneled structures. Others, including those on this continent, compromise by providing partial protection with a membrane over the roof and, perhaps, down the sides of cut-and-cover structures. Water bars are provided at the structural joints, segmented tunnel linings are caulked in the joints to minimize water seepage, and cast-in-place tunnel linings generally are not protected. Common approaches to providing partial and complete membrane waterproofing are indicated in Figures 5-3 and 5-4 for typical cut-and-cover and tunneled structures. Water seepage that cannot be stopped by these means is canalized into the structure drainage system. At the best, this is only a temporary expedient, and it generates additional continuing maintenance.

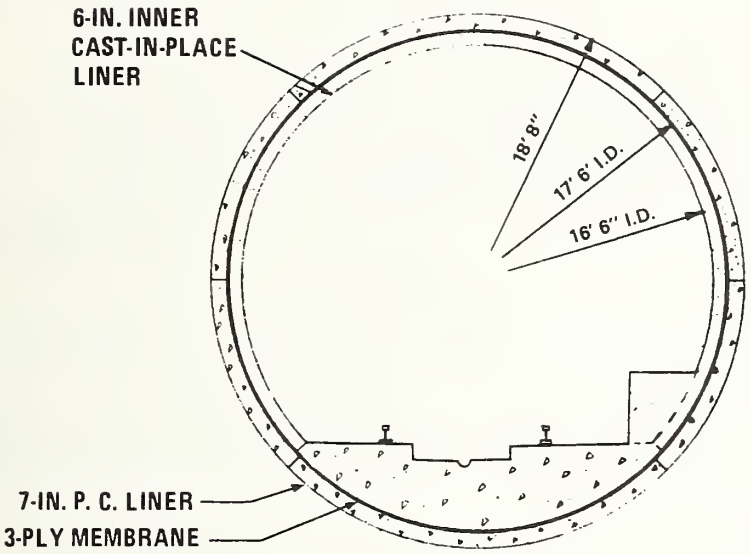


PARTIAL MEMBRANES

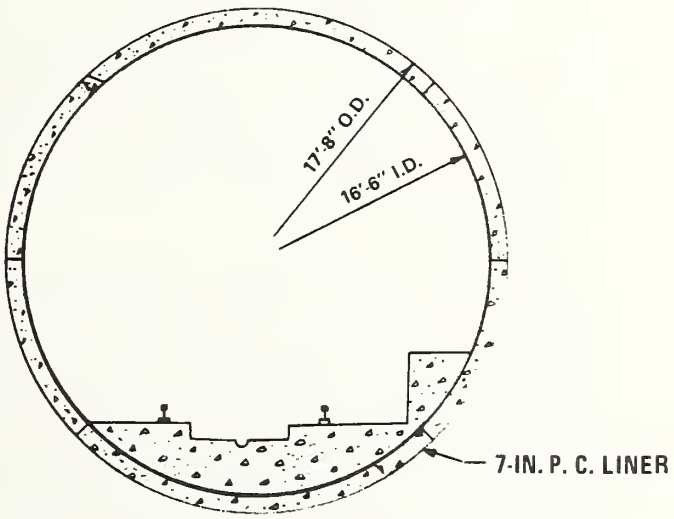


SYSTEM 2
COMPLETE MEMBRANE

Figure 5-3. CUT-AND-COVER WATERPROOFING



WATERPROOFED WITH 3-PLY MEMBRANE AND
6-IN. CONCRETE INNER LINING – SYSTEM 2



GASKETED AND CAULKED JOINTS – SYSTEM 1

Figure 5-4. TRACK TUNNEL WATERPROOFING SYSTEMS

Materials. Three principal materials, or groups of materials, have been used to waterproof subway structures. They are compared and evaluated below:

Coal tar enamel applied in several layers with fabric reinforcement in between: This method has a good performance record for more than 50 years in waterproofing subways, building basements, and the like. It is virtually inert to attack from all chemicals likely to be encountered in the soil and water in which subway structures are located. In addition, two definite advantages arise from the multi-ply system: (1) the laps between the sheets, which are a potential source of leaks, are staggered over the various plys, and (2) the multi-plys and the relatively greater thickness of the final membranes (over the single-ply membranes) provides much greater insurance against puncture during installation.

Bentonite contained between soluble cardboard panels: The sealing action arises both from the bentonite material being moved by water pressure into and filling the cracks and fissures and from its providing a continuous impervious membrane. In principle and in practice, this seems to be a very effective method. As far as can be ascertained, the bentonite is virtually proof against chemical attack. The installation is simple, fast, and economic. However, it is not dielectic, i.e., it will conduct stray currents, and details of installing the panels under the structural invert do not appear to have been developed yet. Its use is also limited to nonsaline groundwater.

Single thickness plastic or artificial rubber sheets: These include polyethylene, polyvinyl chloride, hypalon, neoprene, and butyl rubber. Under nearly all anticipated ground and water conditions surrounding a subway structure, all of these materials would probably exhibit long lasting properties. However, actual experience is limited to the last 30 years or so, and whether they would perform satisfactorily up to 150 years is unknown. The single sheets are bonded to the structures and to themselves by lapping the edges and using appropriate adhesives.

As compared with coal tar multi-ply and bentonite membranes, the relatively thinner single sheet membranes have the disadvantage of requiring added care in preparing the concrete surfaces to remove all sharp

edges and roughness and in installing to prevent puncture. In addition, if the lap joints are not sealed perfectly, water will migrate under the sheet to seep through the structure. Using soft butyl rubber backed by polyethylene is advantageous in obtaining a satisfactory seal.

A more detailed discussion on waterproofing materials and some of their physical properties and resistances to degradation is contained in Appendix E.

Installation. Membranes are generally applied directly to the roof area and walls of a cut-and-cover structure and to the inside of the primary lining of a tunnel. Alternatively in cut-and-cover construction, the membrane can be fixed to the wall formwork (which is supported against the excavation shoring) and the wall concrete placed against it. Where the invert is waterproofed, the membrane is placed on the site concrete before placing the invert concrete. Such details and construction methods are indicated in Figure 5-3. Special details are required for waterproofing structure penetrations such as sleeves and pipes.

Generally, it is considered important to protect the membranes with concrete block or plywood for the walls and concrete on the roof to prevent mechanical damage during backfilling or subsequent excavations.

Tunnels

For cast-in-place tunnel structures to resist the water pressure against the membrane, a secondary (inside) concrete lining is placed directly against it. If the membrane is competently installed (requiring strict control of water seepage through the primary lining during the installation of the membrane until the secondary lining is in position), an essentially dry and maintenance free tunnel can be obtained.

In segmented lined tunnels, minimizing maintenance of tunnels constructed either with steel or concrete prefabricated segments requires correct design of the waterproofing system, selection of the best materials (especially

important for concrete), protective coatings for metal, and ensurance of proper tolerances in the segment manufacture. Some general principles of what appear to be current good design practice for both metallic and concrete segmented linings follow. For a detailed discussion on the subjects for precast concrete, see DOT-TST 75-102.

Waterproofing in Segmented Lined Tunnels. Leaks generally occur in segmented tunnel linings at the joints between segments and at bolts rather than through the segment material. There are four systems that, individually or collectively, can make a segmented lined tunnel essentially watertight. These are:

> Tail Space Grout. This consists of an annular ring of gravel and grout or, alternatively a grout only, which is injected during erection through the segmented lining in the tail of a protective construction shield. If this annular grouted ring is homogeneous and impervious, a watertight barrier will be formed that will prevent water seepage through the segment interfaces. The tail space may be filled by two methods: (1) first by pea gravel (as each ring is erected) close to the face of the tunnel followed some time later, and at a distance from the face, by a second injection of cement grout; or (2) a one-time injection of grout that may be composed of cement, sand, bentonite, and other materials, placed immediately behind the last ring erected.
>
> The first method is suitable for tunnels in very hard ground or soft rock that will not fall into the tail space as it appears and will not mix with the pea gravel when it is injected into the annular void under high pressure, making uniform penetration of the contact grout impossible and preventing the development of an impervious annular ring.
>
> The second method is highly desirable for soft ground and, with proper grout formulations and injection sequences, will go a long way in making the tunnel watertight.
>
> Tunnels surveyed that had been constructed using the second grouting method proved to have a much lower incidence of seepage than those which had been constructed using the first.

Gaskets. Segment face gaskets of elastomeric materials to be applied to either two or the four faces of the segment prior to its erection in the ring appear to be fast becoming accepted by tunnel engineers. Essential features of the gaskets are (or should be):

They seal by compression, either against each other when they are placed on four faces or against the concrete of the opposite segment when placed on two,

The gasket elasticity should be sufficient to permit a certain amount of movement between the segment face and still maintain adequate compression across the segment face to resist groundwater pressure,

The formulation of the elastomeric material should be such that the compression across the segment faces will not sensibly reduce with time, and

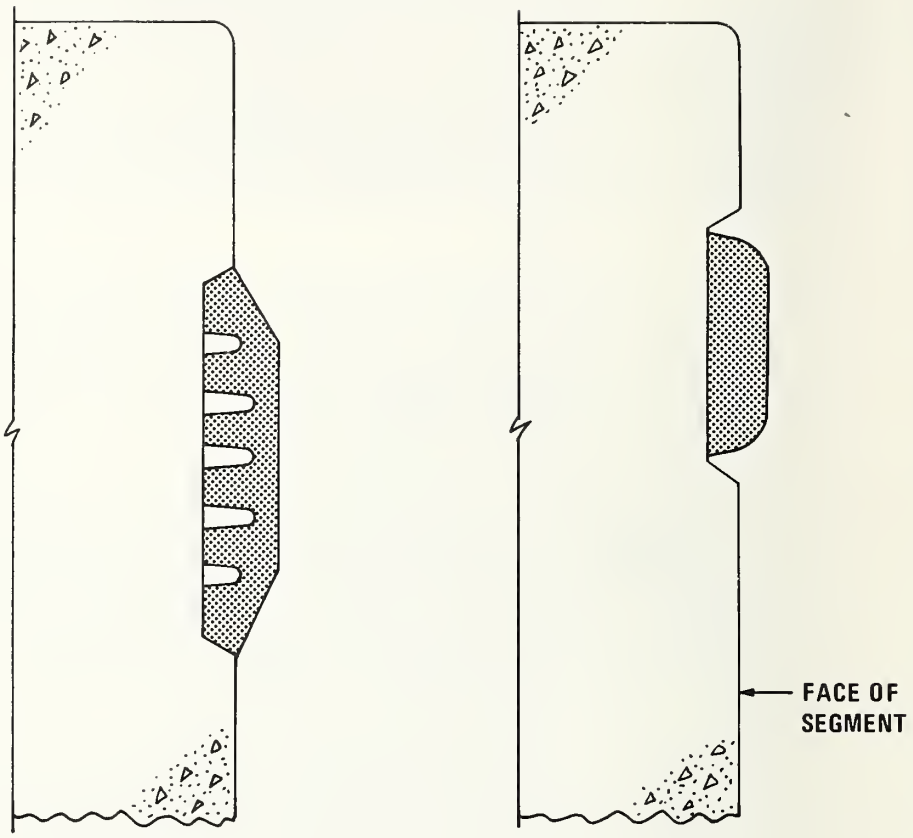
The gasket should be placed on the earth face of the segment bolt circles.

Two typical gaskets are shown in Figure 5-5.

Caulking. A standard method for sealing segmented linings is by installing caulking in grooves, in the inside edges of the segments. Lead has predominated as a caulking material in most metallic lined tunnels in London; elsewhere, expanding cement mortar and epoxy mortars have been used.

Success with these materials requires that installation be done in dirt free grooves with the proper width of caulking tools to provide adequate compaction. In addition, because of the almost complete inelasticity of these materials, it is important that the segment interfaces are bolted tightly together to prevent opening of the joints by ground movements or seasonal temperature changes (particularly near portals). If this is not done, seepage and subsequent maintenance of the caulked joints cannot be avoided.

During engineering of the San Francisco BART system, two elastic caulking systems were developed in a laboratory, and test installations were made in one steel lined tunnel. The first system consisted of neoprene rectangular strips inserted and bonded with especially formulated epoxy into the caulking groove. The second comprised caulking an expansive (when wetted) yard into the groove and sealing it in place with epoxy. Both



DETAIL 1
AFTER WAYSSE & FREYTAG
"TUNNEL CONSTRUCTION IN MUNICH"

DETAIL 2
CARACAS METRO

NOTE:
THE GASKETS ARE CONTINUOUS
AROUND THE FOUR FACES.

Figure 5-5. GASKET SYSTEMS

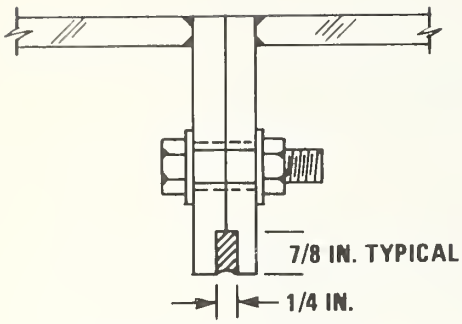
systems proved satisfactory in preventing water inflow and, with development of the necessary equipment, promise to become satisfactory economic systems. Details are given in Appendix F. The various caulking systems discussed above are illustrated in Figure 5-6.

Bolt Grommeting. When principal reliance for water tightness is placed on caulking the inside perimeter of the segments, grommets must be inserted between the head and nut of the bolt and the segment flange faces. The traditional grommet was hemp impregnated with linseed oil and white lead. The softness of this grommet permitted tightening, even with low tension bolts, to allow essentially metal-to-metal contact to be attained. It was found with these grommets little leakage occurred at the bolt and, furthermore, the bolt and the segment faces did not work loose to generate leakage through the caulking.

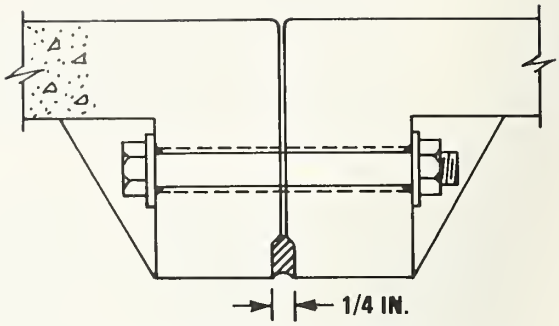
In recent years there has been increasing use of a plastic polyethelene grommet of a hardness that has made metal-to-metal contact difficult to obtain, and impossible when the material extrudes under the bolt washers. This appeared to be the cause of a large incidence of bolt leakage, as well as failure of the segment caulking, through the gradual relaxing of the bolt tension because of plastic flow of the grommet material. Good design practice therefore requires that the grommet should be of a relatively soft, flowable material that will not harden under compression.

Materials. Because stresses arising from both erection and service loads are nearly always very high and some of the loads can produce relatively large strains on the tunnel lining and segments, ductility of the materials is an obviously desirable quality. In this respect cast iron is deficient, but cracking can be limited by the use of small segments and machining the contact faces, or by using defined line bearings, controlling jacking loads, and limiting the use to installations in firm ground.

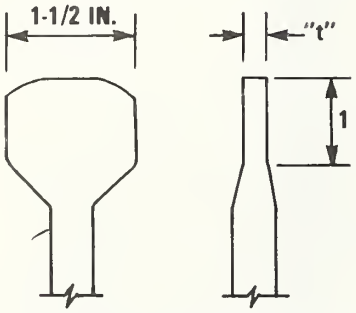
Ductile iron, a newer material than cast iron, has much greater ductility and strength and is much more desirable, particularly in weak or plastic ground situations.



METALLIC SEGMENT
LEAD CAULKING

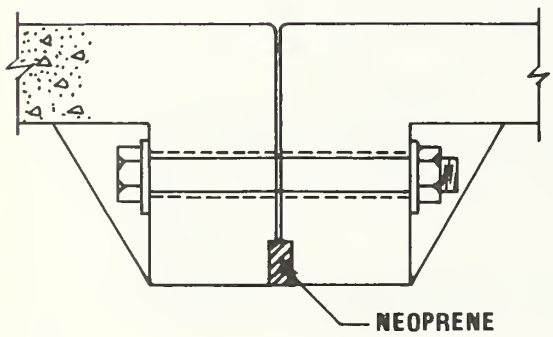


CONCRETE SEGMENT
ASBESTOS CEMENT CAULKING

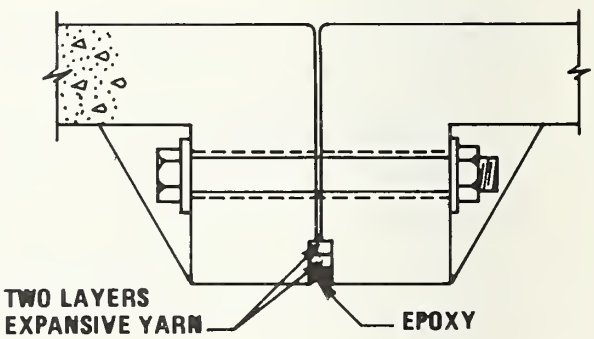


NOTE:
WIDTH OF CAULKING HEAD "t" SHOULD NOT EXCEED 1/32 IN. LESS THAN WIDTH OF GROOVE.

TYPICAL CAULKING HEAD (AIR TOOL)



NEOPRENE COATED WITH EPOXY
BART TEST DEVELOPMENT #1



EXPANSIVE YARN WITH EPOXY "KEEPER"
BART TEST DEVELOPMENT #2

Figure 5-6. CAULKING SYSTEMS

Fabricated steel has considerable ductility and in a tunnel lining can often be deformed far beyond its elastic yield and still support loads satisfactorily. However, unless the welds uniting the components of the segment are properly designed and executed, they can be fractured under excessive strains and, therefore, are one of the critical design and execution items in these segments.

Reinforced concrete has 10 to 25 times the elasticity of steel or cast metal and, when the reinforcing steel is properly proportioned and detailed, exhibits considerable ductility. However, the edges of the segment flanges are vulnerable to cracking and spalling under concentrated loads, and it is, therefore, important that the design be detailed to avoid such concentrations.

Tolerances. Tolerances in the design and manufacture of tunnel segments were generally considered extremely important by the design engineers and contractors interviewed overseas and in this country. This was particularly so in the case of concrete for reasons both of ease of assembly in the tunnel as well as ensuring that the high unit pressures on the radial faces from the permanent ground loads, and on the circle faces from the shield jacks, would generally be distributed across the segment face and not be transmitted on high spots, corners, or edges to cause failure of the concrete.

CORROSION OF STEEL ENCASED IN CONCRETE

Transit subway structures are within a damp and often corrosive environment (including ever present stray electric currents), and attrition by corrosion on embedded structural and reinforcing steel is always a possibility. This is particularly true for the steel mat on the earth face side of the structure when direct inspection of the surface is generally not practicable. None of the transit properties inspected experienced major structural distress of their structures through corrosion of the

reinforcing or structural steel, although no attempt had been made to verify structural conditions on the earth face. In San Francisco, some of the steel lined tunnels are being monitored for corrosion. The three or four properties overseas whose structures are waterproofed on the outside naturally did not experience this problem.

It would appear that for subways constructed in aggressive groundwater and in potentially unstable ground conditions, actions should be undertaken for monitoring steel corrosion or for protecting the steel cathodically or by applying coatings.

The resistance of reinforcement, or other steel embedded in concrete, against corrosion lies principally with the corrosion inhibiting alkaline properties of the cement. Steel begins to corrode when the concrete is heavily cracked, is chemically attacked, or becomes depleted of its protective alkalinity. Where these effects are localized, differential aeration and differential pH concentration cells are developed that promote corrosion of the steel. Another major cause of corrosion in steel reinforced structures is stray electrical current. Direct current causes more severe corrosion problems than do induced alternating currents. Common dc interference sources are generally nearby cathodic protection systems and dc traction transit systems.

Corrosion Monitoring

The standard corrosion monitoring methods such as weight loss coupons, corrosometers (corrosion rate meters), or galvanic current meters are not well suited for long-term surveillance of steel in concrete. These systems are best used for liquids rather than for structures, the conditions of which are difficult to duplicate by the coupons and placement or retrieval of test sections and probes may be a problem.

Most corrosion studies of steel in concrete have been conducted in cement slurries and with precast sections immersed in various corrosive

solutions. The basic measurements taken in these tests were electrochemical polarization measurements dealing with changes in electrode potentials and pH of the solution. Direct relationships have been obtained of which the most useful in terms of corrosion surveillance is the measurement of electrochemical potentials. Test results have shown that potentials of rebars that don't corrode tend to stabilize in a "noble" direction from initial values of between -0.400 and -0.600 volts towards a potential of approximately -0.200 volts (as measured versus a copper sulfate reference electrode). Where rebar corroded, the potential drift was in the active or more negative direction.

The technique of corrosion monitoring of steel in concrete has been used in corrosion surveys of prestressed concrete pipelines and wire-wound prestressed concrete reservoirs. Other nondestructive methods including vibration, resonance, pulse propagation, radioactive, and magnetic methods are still in exploratory stages and have not yet gained any universal acceptance. These methods also require direct contact with the exterior of the concrete structure and may be difficult to use on buried systems where corrosion problems are localized.

Corrosion Monitoring for Subway Structures

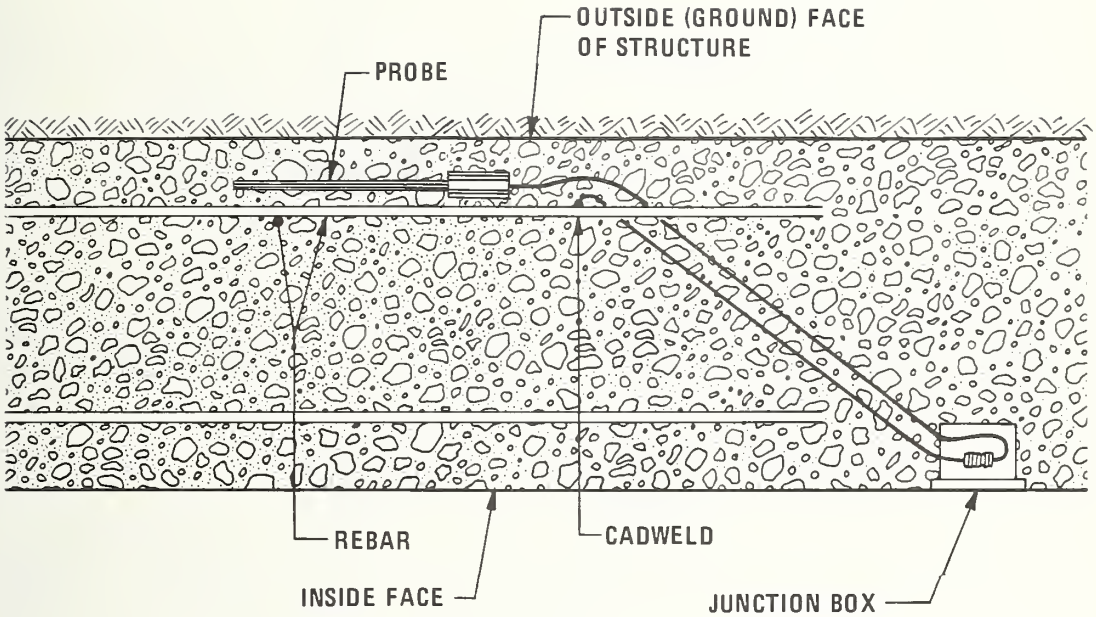
Techniques are available for measuring electrochemical potentials applicable to steel reinforced concrete tunnel structures. Where conditions warrant, instrumentation for corrosion monitoring should be installed and provisions for the later installation of cathodic protection should be made (if the onset of corrosion be detected). The initial provisions for future installation of cathodic protection require welding the outer layer of rebar or other steel for electrical continuity in cut-and-cover structures and in segmented tunnel linings as well, providing electrical bonds between the segments. The instrumentation consists of: electrolysis test stations spaced to obtain a potential profile of the buried structure and providing electrical leads from ground surface to the rebar (or other

steel) for connection to the future installed anodes for a cathodic protection system should the need arise.

The corrosion monitoring program would involve scheduled time periods where the electrical potential profiles of the structure would be logged and current interference tests made to detect stray currents. These data would then be compared to determine areas of probable corrosion activity. The term "probable" refers to the fact that while the potential in an area is shifting toward a more active value (i.e. positive), corrosion does not usually occur until the reserve alkalinity in the concrete has been depleted. If the need for corrosion control is indicated, installation of a properly maintained system would protect the rebar (or other steel) from additional corrosion. However, corrosion protection does not afford protection to the concrete itself if it comes under direct chemical attack.

Monitoring Systems. A system recently developed by Matcor, Inc. (the Matcor Corrosometer) for monitoring corrosion of reinforcement in bridge decks has application for subway structures. It consists of a thin steel probe cast into the structure close to the reinforcing steel and connected by electrical leads through a junction box on the inside face of the structure to the rebar mat on the earth face. Periodic readings by a resistance measuring instrument are made of the resistivity of the probe to ascertain if corrosion is occurring in the probe, which is considered to react similarly to the rebar which is in the same environment. The measurements are confined to the length of the probe and, therefore, a number of installations are required in fairly close proximity in suspect locations in the structure to obtain representative information. Figure 5-7 indicates a typical probe monitoring installation.

A second monitoring system measures the electrical potential between the exterior layer of rebar in a subway structure and a zinc anode placed in



SECTION PLAN OF WALL

NOTE:

1. LOCATE THE PROBE AS CLOSE AS POSSIBLE TO THE REBAR WITHOUT TOUCHING IT.
2. CADWELD THE GREEN GROUND CABLE TO THE REBAR.
3. COIL THE PLUG AND SLACK CABLE IN THE JUNCTION BOX OR RECEPTACLE.

Figure 5-7. CORROSION MONITORING INSTALLATION

the ground approximately 5 feet from the structure. The essential details of the system are shown in Figure 5-8. The terminal box, from which the periodic monitoring readings are taken with a potential meter, is indicated at ground surfaces, but it may be mounted within the underground structure.

This system would monitor the potential of the steel in an area of approximately 5 feet in diameter; i.e., equal to the distance of the anode from the structure, but probably does not provide as specifically accurate information as the first system discussed. The system is described in detail in Appendix G.

Monitoring Corrosion of Metallic Tunnel Linings. An ultrasonic thickness gauge can be used to effectively monitor corrosion on the earth face of steel or cast iron tunnel lining where the inside surface of the metal is exposed (i.e., no secondary lining). The principle of this method is that when ultrasonic wave pulses from one side, or face, are propagated through a homogeneous material, they are reflected when they encounter a second surface boundary or discontinuity. The distance between the first and second surfaces is determined by measuring the time between propagating the wave and receiving its reflection back at the source.

There are several suitable portable ultrasonic thickness measuring instruments on the market. These typically consist of a probe head that both transmits the propagated wave and receives the reflection. The probe is connected by cable to a battery powered instrument that displays the thickness reading on a dial face.

Corrosion Control by Cathode Protection.

Once it is determined that steel reinforcing bars in concrete structures or tunnels with metallic linings are corroding, an effective method of

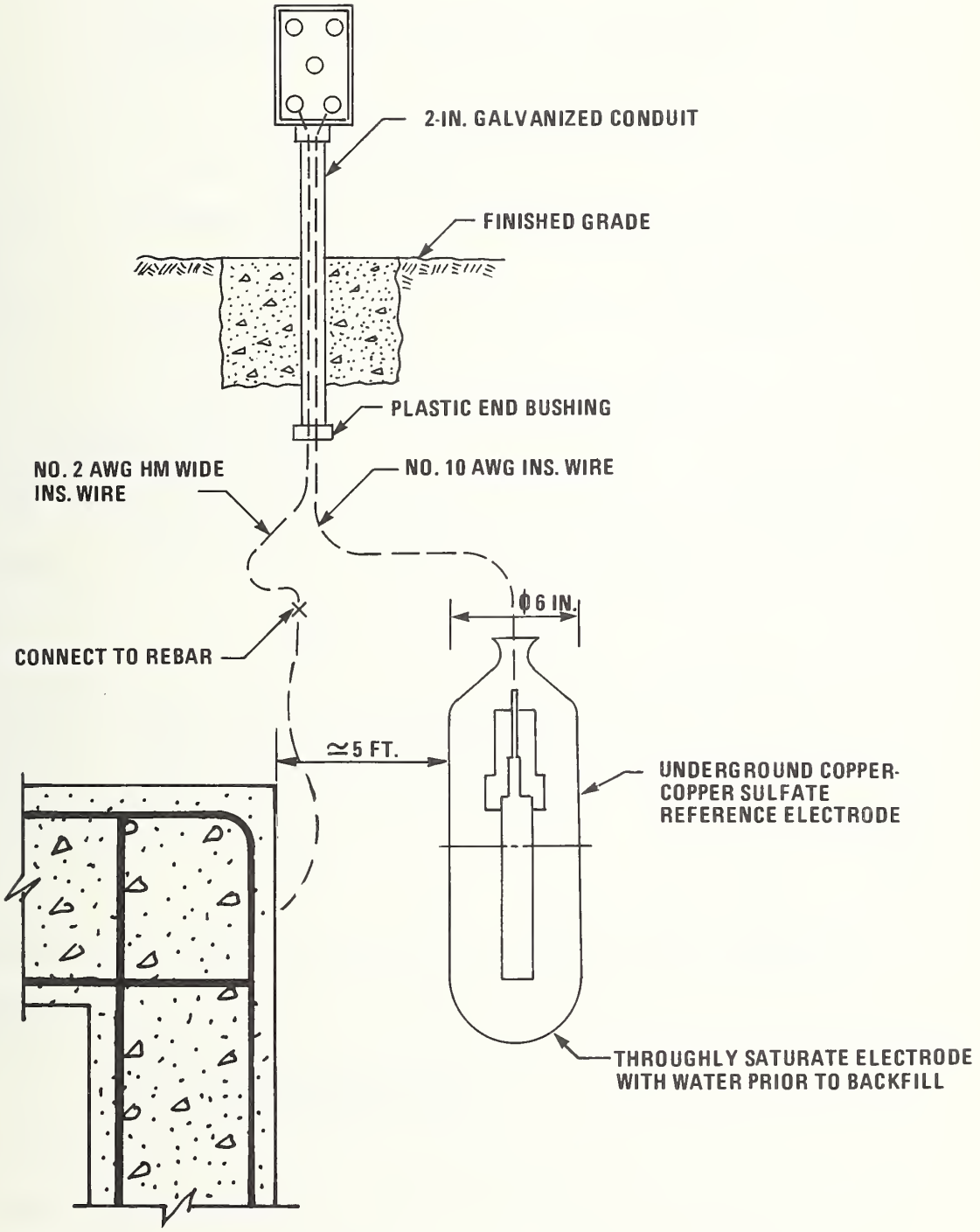

2-IN. GALVANIZED CONDUIT
FINISHED GRADE
PLASTIC END BUSHING
NO. 2 AWG HM WIDE INS. WIRE
NO. 10 AWG INS. WIRE
Ø6 IN.
CONNECT TO REBAR
≃5 FT.
UNDERGROUND COPPER-COPPER SULFATE REFERENCE ELECTRODE
THROUGHLY SATURATE ELECTRODE WITH WATER PRIOR TO BACKFILL

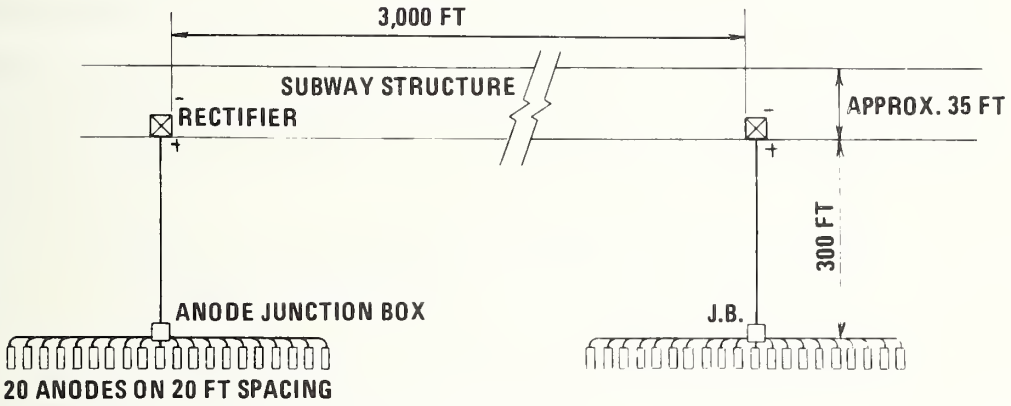
Figure 5-8. TYPICAL REFERENCE ELECTRODE AND TEST STATION

corrosion control that does not require extensive excavation is cathodic protection. Essentially, cathodic protection involves application of direct current to reverse the electrolysis of steel. To ensure that all corroding areas are adequately protected, as mentioned previously, all reinforcement must be made electrically continuous by tack welding the individual bars, and the tunnel segments must be electrically bonded together. The current required for protection of reinforcement ranges from 50 to 150 microamperes per square foot of steel surface area. For design purposes, the surface area to be protected is generally estimated as equal to the steel area on the ground side of the concrete structure only. The outer layer of reinforcement effectively shields inner bars from receiving current. Cathodic protection that provides a polarization in the range of -0.700 to -0.850 volt (versus copper sulphate reference electrode) will arrest any corrosion activity. Excessive polarization beyond -1.1 volts is to be avoided because of hydrogen evolution which can reduce adhesion of the concrete to the rebar.

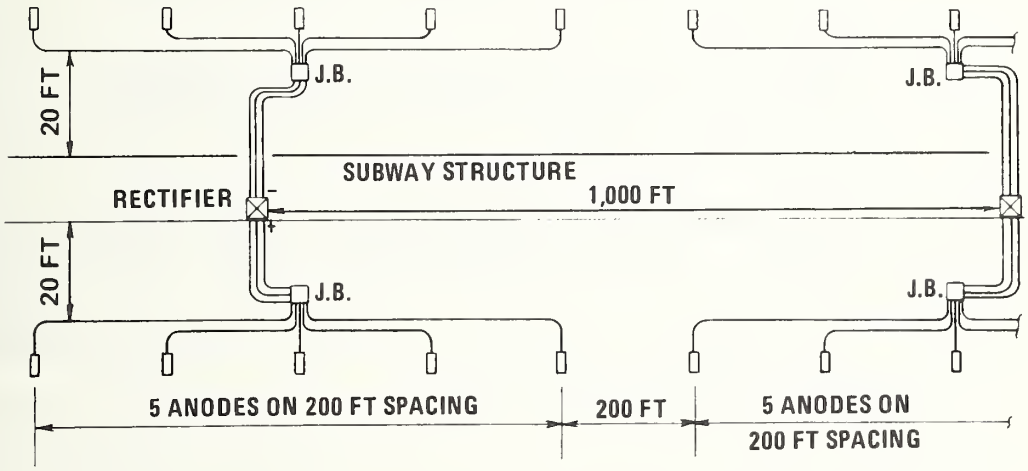
A cathodic protection system basically consists of a series of banks of sacrificial anodes, often of zinc, installed outside the subway structure and interconnected through a junction box to a dc power source and to the steel to be protected. A typical arrangement of the components is indicated in Figure 5-9.

A number of variables, which may change from location to location in one transit system, affect the actual sizing and arrangement of the components and power source. The variables include the surface area of the metal to be protected; the degree of aggressiveness of the corrosive agents, and the resistivity of the ground. In addition, physical constraints alongside the subway structure, including buildings and utilities, will impose limitations upon the locations of the anode banks. The power source usually is rectified from the auxiliary ac supply within the structure to dc, and then transformed to between 20 and 100 volts depending upon the specific variables. Section 6 contains a cost evaluation between two possible

ARRANGEMENT 1: ANODES AT MAXIMUM SPACING



ARRANGEMENT 2: ANODES ON 200-FT SPACING 20 FT FROM TUNNEL



NOTE:
SEE APPENDIX FOR COST ESTIMATE
OF TYPICAL INSTALLATIONS.

Figure 5-9. CATHODIC PROTECTION LAYOUT AND COMPONENTS

extremes of spacing the anode banks. Further details of this subject are discussed in Appendix G.

Protection of Rebar with Epoxy Coatings. A fairly recent innovation in corrosion protection, apparently in connection with reinforced concrete bridge decks, is coating of reinforcing steel with epoxy. This subject is discussed in detail in "Corrosion of Metals in Concrete," ACI Pub. SP-49; Ref. the most pertinent facts are summarized here:

> The epoxy coating should be applied to metal prepared by sand or shot blasting, by the electrostatic spray method and properly cured. The film should be 7 (±2) mils thick,
>
> Such a coating is sufficiently tough to withstand abrasion and mechanical damage providing certain care is taken during bending, transportation, and fabrication on the jobsite,
>
> Cut ends and accidental damage can be repaired by brush touch up, and
>
> Bond to the concrete appears to be unimpaired by the coating, and it provides an effective barrier against electrochemical attack.

The cost of epoxy coatings applied at the mill varies according to the quantity, length, and diameters of the steel; a rough average for 40 feet of straight lengths 3/4 inch in diameter indicates that the base cost of the steel will be approximately doubled.

Miscellaneous Exposed Steel. This category encompasses a large number of steel items, some of which are partly embedded in concrete such as: brackets, hangers, door frames, manhole frames, etc., and others that are fully exposed including: ladders, stairs, gratings, checker plate, and frames supporting pumps and ventilation fans. Other items, and usually the most important in quantity, are metallic tunnel linings.

In most properties visited, maintenance of miscellaneous metal was an important subject and deserves discussion from two aspects: initial design

(and installation) and subsequent maintenance. Main agents of attack include water seepage through the structure; direct water ingress from the ground through ventilation shaft gratings, emergency exits, and portals; and moist air entering through the same openings.

In general, miscellaneous metal is not exposed to electrochemical attack, but tunnel linings are an exception, as discussed earlier in this section. The following design rules are considered vital to minimize corrosion. Details should be designed for easy maintenance, i. e., recoating. This requires:

> Making all exposed surfaces easily accessible for both preparation and application of the repair coating,
>
> Grinding smooth or rounding all sharp or rough edges, including gas cuts,
>
> Where possible, avoiding pockets and ledges that will collect dust and moisture. Providing positive drainage of all surfaces by, if necessary, building up, inclined planes with properly bonded cement mortar or mastic, and
>
> At the interface of steel and concrete, particularly on horizontal surfaces, building up water sheds with concrete during installation or mastic afterwards. Where concrete is likely to shrink away from the metal, such as at manholes and other framed openings, the junction of metal tunnel linings and the concrete invert, grooving the interfaces and filling with an elastic sealant.

Protective coatings should be selected for their durability and, of course, for their applicability to the particular item in question. Some of the more satisfactory coatings are:

> Hot dip galvanizing provides a relatively thick coat, typically 2 oz per sq ft of zinc, and is usually specified for gratings and other difficult to paint items. It is vulnerable to attack by salt (calcium chloride) and, therefore, potential exposure areas should receive a secondary coat of paint such as chlorinated rubber,
>
> Inorganic zinc silicate has excellent protective qualities and, unlike pure zinc, resists attack from calcium chloride. It is generally applied by airless spray, over a primer, to a thickness of 2 mils. It can also be

applied by brush. For particularly wet or corrosive conditions, a secondary paint coat is advisable.

Epoxy coatings in similar applications to those described for rebar, with or without a secondary paint coat, in all probability would provide a very satisfactory protection for most items under most conditions. However, in none of the properties visited was this system used.

Reliable painting systems appears to give satisfactory and economic service for items exposed to mildly corrosive atmospheres. Suitable paint systems include chlorinate rubber, epoxy based, and red lead (Type IV). All paints should be applied with the necessary primers and according to the manufacturer's specifications.

Preparation of all metallic surfaces before the application of any coating must include thorough cleaning to bright (or bare) metal and providing surfaces dry and free from any impurities. Cleaning methods include shot or sand blasting and acid baths for complex sections.

To repair areas where the onslaught of corrosion has begun, the surface of metal on which the protective coating has broken down ideally should be prepared to bright metal. Suitable portable equipment is available for this surface preparation, for instance the Panli & Griffin Sand Blaster and the Von Arx Needle Scalers of various types (see Equipment List C16 in Guidelines for New Subway Installations). Any of the applicable systems described for the original installation (except hot zinc dip) may be used for recoating with suitable portable equipment.

Most of the engineers interviewed advised that protective coatings should be routinely inspected and repaired before the corrosion began, obviously, to reduce the cost of surface preparation.

ARCHITECTURAL FINISHES MATERIALS AND DETAILS

Architectural finishes used in a station bear directly upon its maintenance costs. In this respect, maintenance engineers of many of the properties interviewed expressed dissatisfaction with some of materials that had been installed, particularly recently, in their stations. This applied not only to new work but also to the refurbishing of existing stations.

Installation methods and design details were also subject to criticism from which could be inferred that architectural designers did not adequately consider the maintenance operations of cleaning, repair, and replacement. The maintenance engineers generally appreciated that aesthetic appearance within the station was important, and the use of newly developed and nontraditional materials must be considered and tried; but in many cases, the materials or the details adopted were clearly inappropriate in the situations where they were used.

Some fundamental principles to guide selection of materials, installation, and detailing that would optimize maintenance activity follow:

Floors.

Figure 5-10, indicating a typical station floor part-layout and Figures 5-11 through 5-15 illustrate the architectural details of this discussion.

The degree of wear on a station floor varies according to the way the pedestrian traffic is concentrated. Three traffic intensities (heavy, moderate, light) have been shown on Figure 5-10 and may be assumed to indicate also areas of frequency of repair and replacement.

In a station of high patronage, given a reasonably hard wearing floor material, Area 1 may be assumed to require replacement every 7 years, Area 2 in 20 years, and Area 3 in 40 years.

From an economic point of view, it might be considered that materials of different durabilities for all the three areas should be selected so that repair and replacement of the areas could be undertaken at approximately the same periods. However, a more practical approach probably is to use one very durable material in Area 1 and use a less expensive material for the remainder of the flow areas.

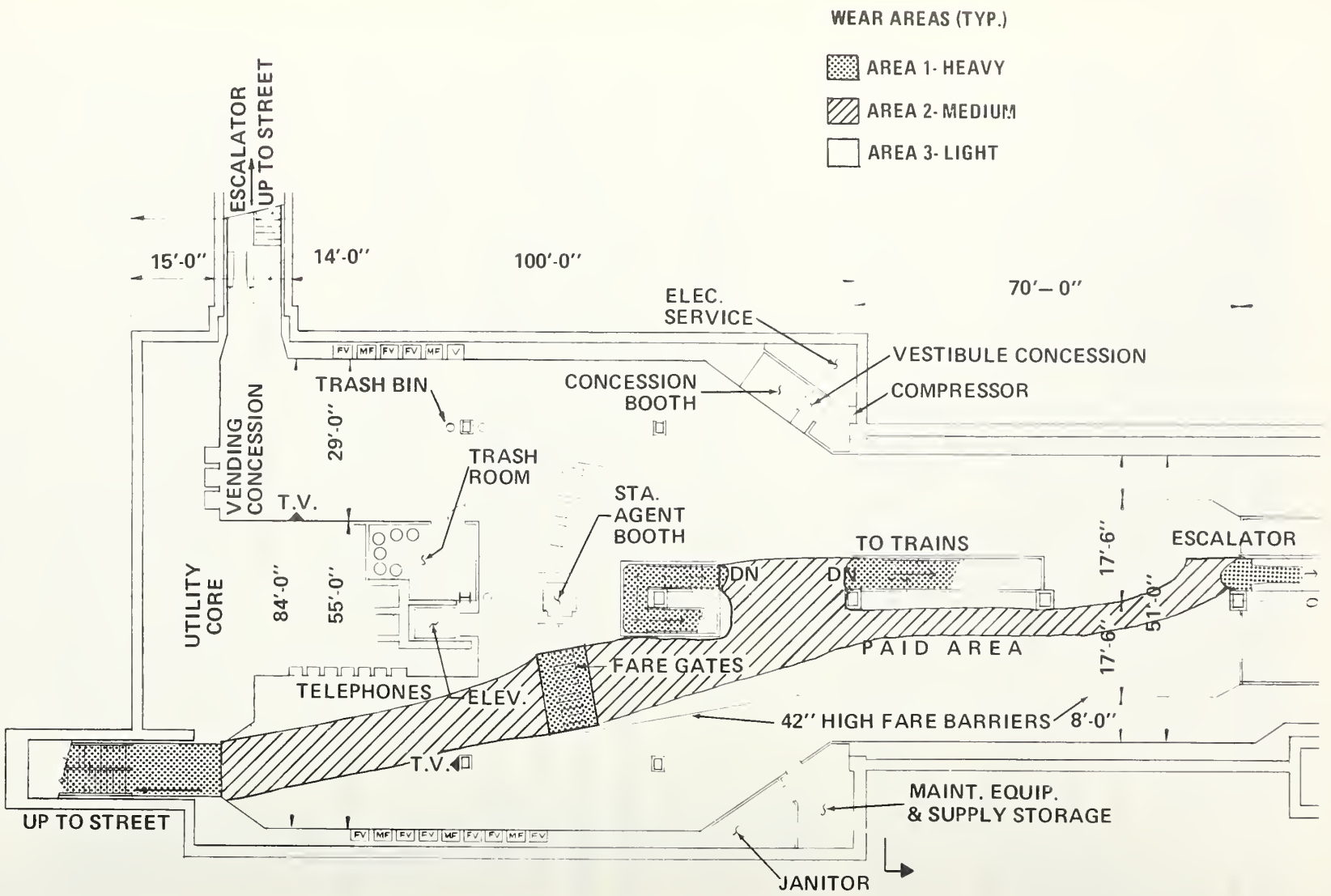


Figure 5-10. STATION PART MEZZANINE PLAN

Because several complete replacements and frequent spot repair can be anticipated over the service life of the station, tiles, paver bricks, or precast units should be used and set with reasonably wide joints to permit ready removal and replacement of any area of the floor within the non-revenue times of the system.

Floor Materials. Materials that have demonstrated satisfactory performance in stations are:

> Quarry tiles, typically 6 ft x 6 ft x 5/8 in thick, are of unglazed burned clay and often incorporate abrasive materials in the surface. Variations in quality exist among different manufacturers across the country. The best quality tile, according to those who have used them, perform outstandingly under the most arduous and concentrated wear conditions, such as on exterior stairways, through turnstiles, etc.
>
> Paver brick (or tile) is usually of common brick dimensions, 1-1/2 inches or 5/8 inch thick with a relatively rought surface. Transit owners report good durability but a little more difficulty in cleaning than for quarry tile.

Detailed specifications of quarry tile and paver brick and the recently developed paver tile are given in "Recommended Standard Specifications for Ceramic Tile," TCA 137-1 1976 (The Tile Council of America, Inc.).

> Terrazzo is composed of natural stone and cement (normally) mortar. The surface is finished by grinding. Wearing qualities appear to depend upon the size and type of aggregate (the harder and larger the aggregate, the better the wearing characteristic). For conditions of moderate to light wear, transit owners appear to be satisfied with terrazzo providing it is properly installed. As discussed previously, the precast tile form is more practical for replacement than cast-in-place in a busy substation.
>
> The National Terrazzo and Mosaic Association, Inc., provides a detailed discussion on the various types of terrazzo in present day use and

provides guidance for its installation and good-practice details.

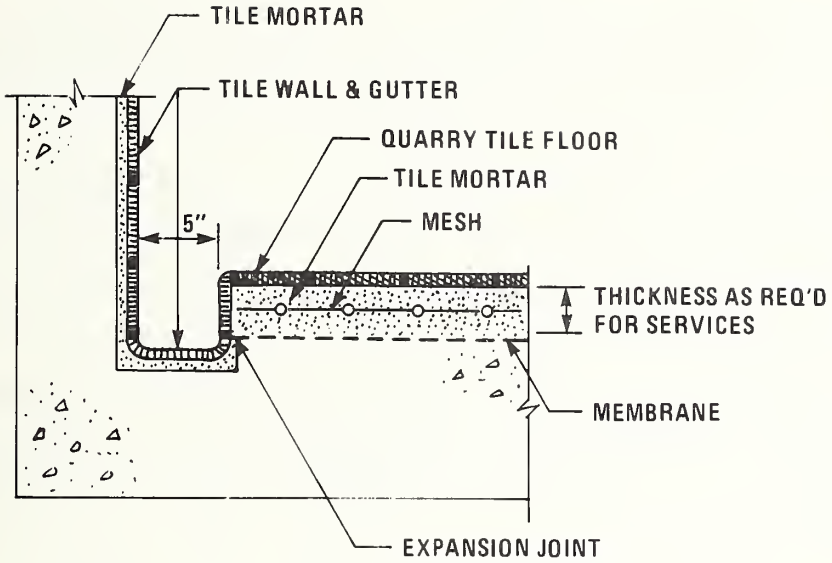
Tile and Paver Brick Installation. In the installation of tile or paver brick floor on structural concrete slabs, three items (under-mortar bed, tile mortar, and construction details – such as expansion joints) are important. The 1976 Handbook for Ceramic Tile Installation (Tile Council of America) provides guidance for mortar material selection and details for various service requirements. Some details are typified for appropriate subway stations use in Figure 5-11.

Details for Ease of Cleaning. The gutter, Detail 1 shown, was favored at many properties, not only as a drain for the floor and wall wash water but also for preventing unsightly accumulations of debris and difficult to clean corners. An alternative, Detail 2, favored in areas of light traffic, makes use of a baseboard of the same material used in the floor.

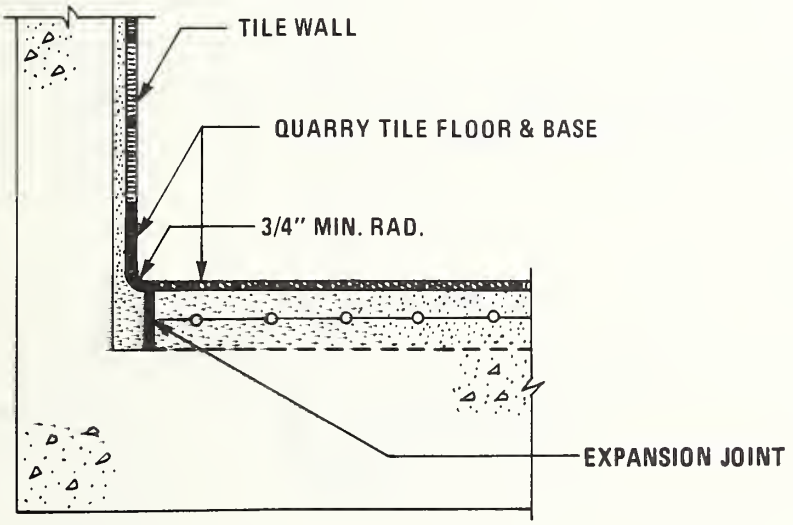
Walls

A general concensus among the maintenance engineers and some transit architects interviewed was that wall finish should be hard and readily cleanable, mechanical damage and defacement from the public being the agent of attrition, rather than abrasion and wear. Normally, structural walls are reinforced concrete (an exception is tunneled structures with metallic linings) and where hard tile, or other similar brittle material is applied directly to the structural face, precautions must be taken against mechanical damage to the finish, such as cracks and edge spalling. These can be generated by differential thermal movements and stress and shrinkage strains in the structural concrete.

Materials. Favored materials from the maintenance aspect were hard glaze ceramic tiles. Semiglaze tiles normally larger than the 6-inch hard glaze and mosaic tile 1-1/2 inches (or smaller) were considered acceptable



DETAIL 1 FLOOR TO WALL – GUTTER

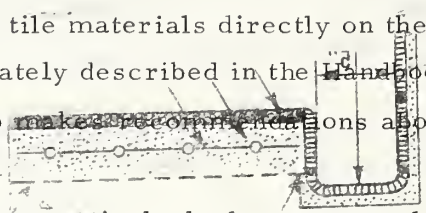


DETAIL 2 FLOOR TO WALL WITHOUT GUTTER

Figure 5-11. FLOOR WALL DETAILS – TILE WALLS

if properly installed. Metal panels, bronze aluminum, and stainless steel with textured or brushed surfaces were also considered satisfactory.

Installation. Installing tile materials directly on the structural face or on false supports is adequately described in the Handbook for Ceramic Tile Installation, which also makes recommendations about mortars and adhesives.



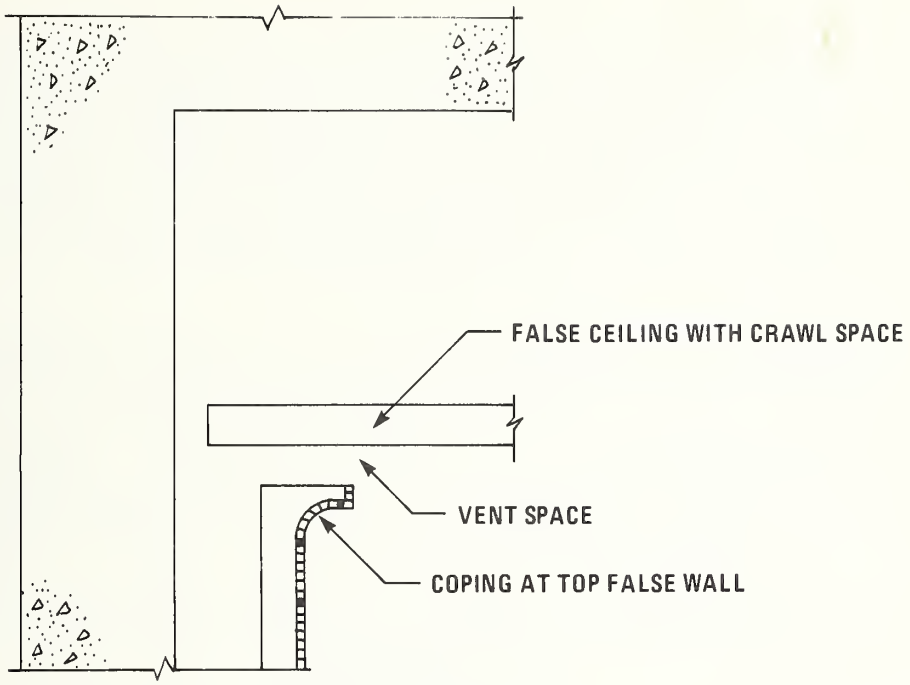
The plasticity of mortar, particularly for structural face applications, is important in minimizing the effects of thermal differentials and structural cracking. The provision of mesh reinforcement in the mortar bed is also helpful.

Details to Aid Cleaning and Ventilation. The most economic system of cleaning walls and ceilings appears to be with high pressure water sprays, where vulnerable equipment is not installed. With directly applied wall and ceiling finishes, cleaning is accomplished without difficulty by this method. However, false wall and ceiling construction requires more thought as to detail. Satisfactory solutions that provide both drainage and ventilation of the space between the wall ceiling and structure are indicated in Figure 5-12, Details 1 and 2.

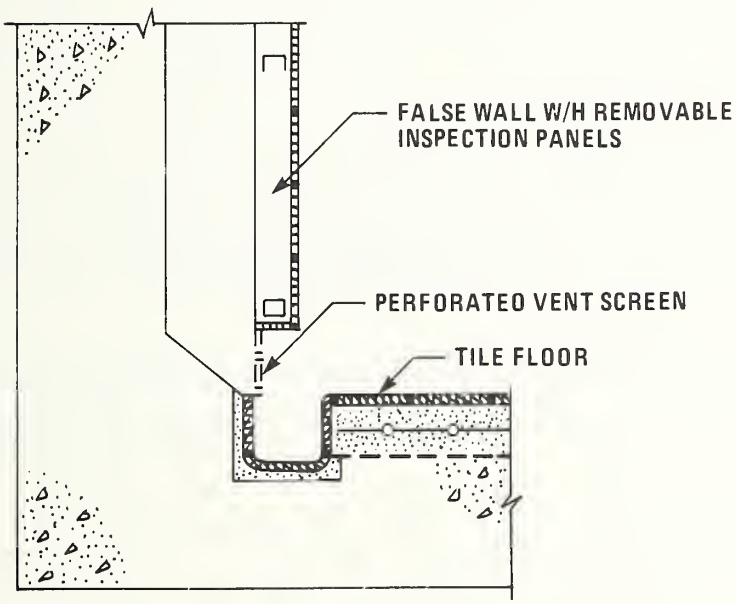
Ceilings

Principal maintenance requirements from a ceiling are ease of cleaning and, if hung, sufficient space from the structure to permit periodic inspection of the structure above. Ventilation of this space was considered important in most cases. The importance of soundproofing, which leads to specifying softer or otherwise more difficult to clean materials, was challenged by some maintenance engineers.

Materials. Those applied directly to the structure, with the exception of acoustic plasters and paint in some situations, were in general considered readily maintainable. Hung ceiling materials, such as solid lath and plaster and asbestos boards, both of which were painted, were deemed



DETAIL 2 FALSE WALL TO CEILING



DETAIL 1 FLOOR TO FALSE WALL

Figure 5-12. FALSE WALL INSTALLATIONS

satisfactory if structure was watertight. Where open ceilings were installed, those of metal or glazed asbestos parallel rectangular (vertically) were liked very well. These combined the virtues of structure ventilation, direct inspection, and easy maintenance; i.e., readily washed and proving satisfactory sound baffling (see Figure 5-13).

Lights. As noted previously, bare tube fluorescent lighting is becoming popular in several of the transit properties visited because it maximizes lighting effectiveness and minimizes maintenance. This lighting form goes well with the parallel bar type ceiling that permits placing the lights between the bars and eliminates side glare. Reflectors can be dispensed with by painting the overlying ceiling white. Figure 5-13 also shows these details.

Stairs. Apart from the requirements for extremely durable tread material, a certain amount of attention was being directed towards the ready replaceability of the tread when the materials did wear into a potentially dangerous condition.

Materials and Details. Figure 5-14 indicates details and the components of the replaceable treads developed farily recently be London, Paris, and Boston for use in some of their most heavily used stations.

In addition to tread details, the provision of a gutter of the type indicated in Figure 5-10, Detail 1, was considered important for maintenance and appearance.

LAYOUT OF STATION AREAS

At all transit properties, the importance was appreciated of designing the stations to permit surveillance by the station agent from his booth of all public areas (particularly those unpaid) and also for ease of

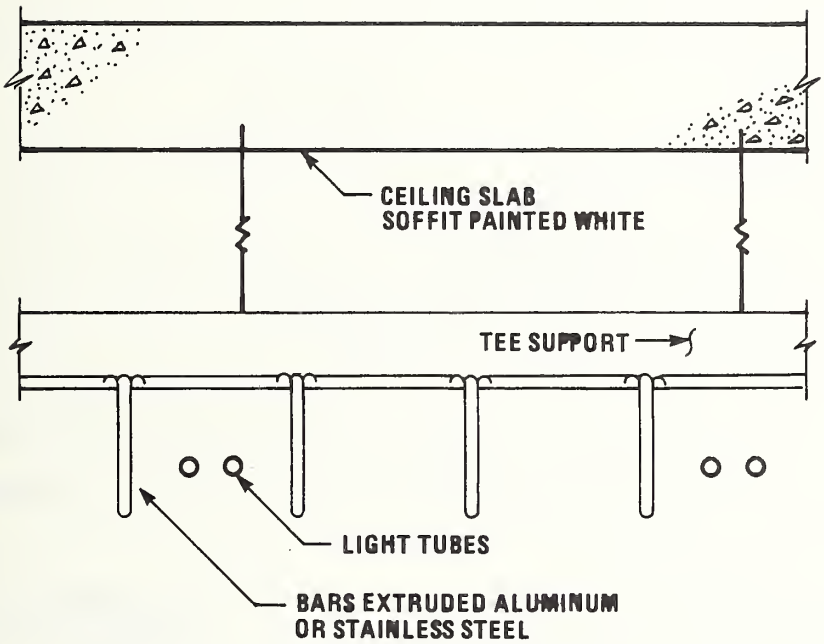
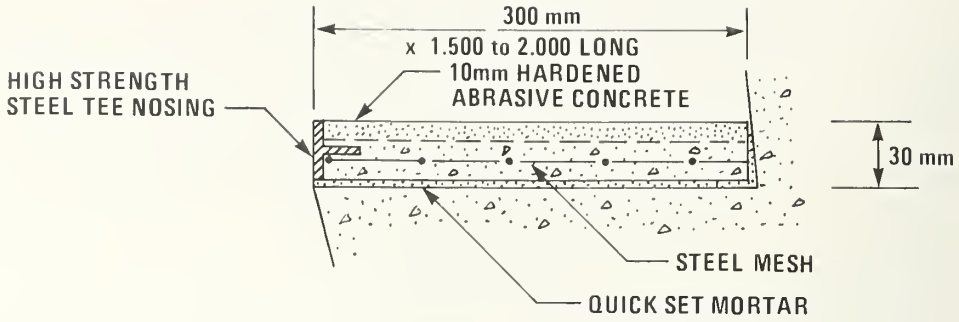
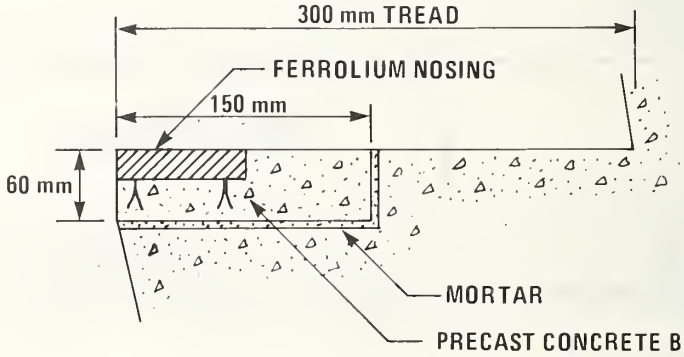


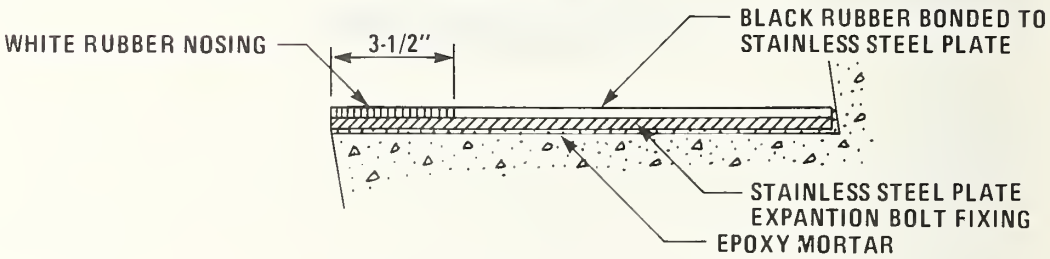
Figure 5-13. LIGHTING DETAILS



PRECAST CONCRETE – PARIS



FERROLIUM NOSING/PRECAST CONCRETE – LONDON



RUBBER/STAINLESS STEEL TREAD – BOSTON

Figure 5-14. PREFABRICATED STAIR TREADS

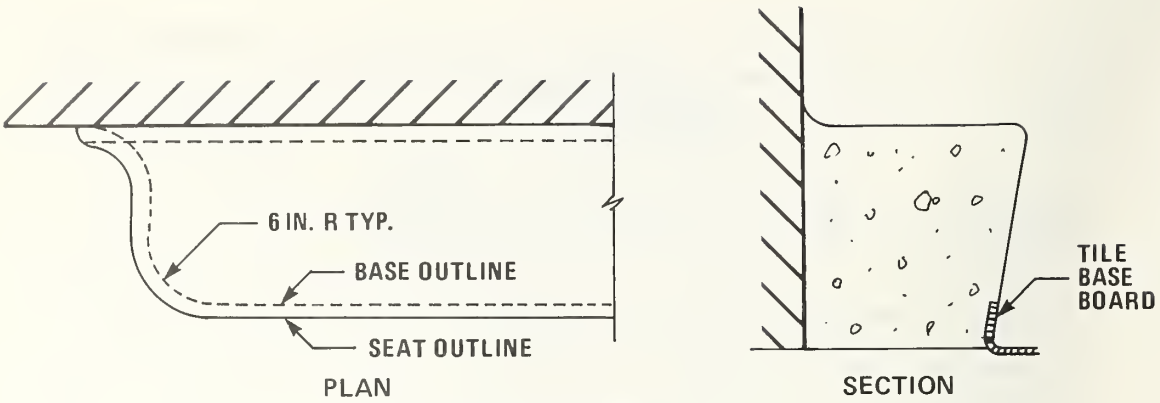
maintenance. The former feature was believed to considerably reduce the incidence of vandalism, and consequent maintenance, and to provide more safety for the transit patron.

Figure 5-10 illustrates some of these desirable planning features and related items. In addition to the fare gates, the important items to be monitored are: the fare vending equipment, the escalators and stairs, the elevator, and, of course, the public floor areas. The location of the agent's booth provides direct line of sight to some of these items. However, both of the street accesses and the areas in which they empty are not directly visible from the booth.

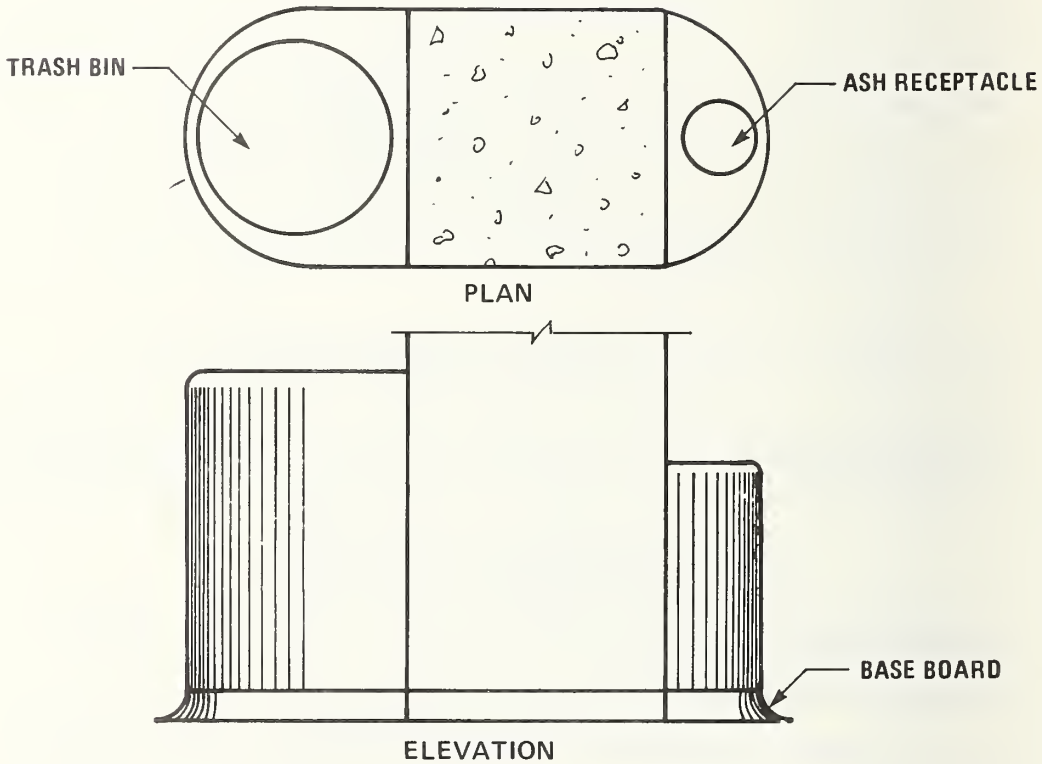
Closed circuit roving TV cameras, located in the positions indicated, would go a long way in correcting this situation and would permit monitoring the stairs and escalators for accidents and the dead areas, including the escalators, for safety and vandalism. However, it is obvious the situation could be improved by rearranging the utility core to reduce, if not eliminate altogether, the visually dead areas.

By flaring off some of the reentrant corners, floor maintenance by machine has been facilitated, but some undesirable pockets around the vending concessions, the telephones, and the two columns flanking the escalator to the trains still require hand cleaning.

To further assist cleaning, particularly by machine, floor mounted items and columns should be detailed without sharp corners and arranged so that hard-to-get-at dirt collecting spaces are minimized. Two examples of such details are illustrated in Figure 5-15. Detail 1 indicates possible details of a wall bench, the principal features of which are the solid cross section (to avoid rubbish collecting and difficult cleaning of the cantilever type) and the tile baseboard. Detail 2 shows trash and ash receptables combined with the column to avoid the undesirable arrangement indicated in Figure 5-10.



WALL BENCHES
DETAIL 1



RECEPTACLE DETAILS
DETAIL 2

Figure 5-15. FLOOR-MOUNTED ITEMS DESIGNED FOR EASE OF MAINTENANCE

Several maintenance engineers mentioned the inadequacy of storage space in their stations for maintenance equipment, supplies, and trash handling and storage. These are provided for in Figure 5-11 as is an elevator that is close to the trash storage area and serves street and platform areas.

6 ECONOMIC EVALUATION TO OPTIMIZE ENGINEERING DESIGN DECISIONS

The economic design of a transit subway complex requires the resolution of alternative choices between cost and performance for all items that compose the complex. For many of the minor items, alternatives are few and selection can be made subjectively. Others bear directly or indirectly upon immediate or long-term costs and require in-depth evaluation to arrive at an optimum solution. This section discusses the general principles involved in such evaluations and provides three examples to illustrate the application of these principles.

DEFINITION OF COSTS

Every item of a subway complex has two costs during its useful service life. The first is the installed cost, i.e., capital charge; the second is the cost of maintenance (including repair) required to keep it in satisfactory condition until it has to be replaced. These two costs make up the real cost of an item.

Nonperformance is a third and indirect cost that also affects the real cost of an item. This is the effect of the nonperformance of one item increasing the maintenance costs of other items, and these costs must be added to the real cost of the nonperforming item. A typical example is a leaking structure that increases the maintenance costs of wayside equipment, architectural finishes, etc. Another example is bad performance of floor and stair material or escalators that continually hinder and inconvenience passengers to the extent of adversely affecting the patronage of the system.

Present worth costing is a method of adjusting anticipated future costs to present day values. These costs, added to the installed cost, indicate the real cost of an item (or operation). The components of a real cost calculation include:

1. The installed cost of an item,
2. The cost of maintenance (and repair) over its useful service life, and
3. The costs effect of its nonperformance on other items.

Item 1 is the cost of the item at the date of installation or entering service. Item 2 represents future periodic costs from date of installation. To account for the decreasing value of money over the years, these costs are adjusted to present worth values on the basis of estimated annual differences between the inflation rate and the rate or cost of money to the transit property. Item 3 is the nonperformance impacted costs in the future on other items, adjusted to present worth values.

METHODOLOGY

The service lives and replacement periods for the items that compose the subway complex vary widely as do their maintenance costs. The present worth cost method, also termed discounted cash flow method of analysis, recognizes the time value of money and assigns a lower value to costs anticipated in the future than to costs occurring at the present, because money invested now to cover future costs will be less than the expected cost since interest would accrue on the investment. The amount of money that would have to be invested at the present time to cover future costs is a function of the interest rate and time (interest periods). Calculating the present worth of these future costs is called discounting, hence the term discounted cash flow.

In comparing alternatives, all anticipated costs — annual and nonannual — are discounted back to a present worth value to put them all on an

equivalent basis. The summation of the present worth of the costs for each alternative can then be compared to permit selection of the least cost solution.

The following is a standard formula for expressing present worth:

$$P = F \left[\frac{1}{(1 + i)^n} \right]$$

Where: P = represents a present sum of money at the beginning of the first of n periods; i.e., it is the discounted value of a cost incurred in the future. P/F is termed the present worth factor,

F = sum of money to the end of n periods that is equivalent to P at interest i,

i = interest rate per interest period (in the formula it must be expressed as a decimal), and

n = number of years or interest periods.

This formula can be applied to expected costs for each year of the analysis. Formulas are also available for items, such as maintenance, which are the same each year throughout the period of evaluation. The formula for a uniform series of costs is:

$$P = A \left[\frac{(1 + i)^n - 1}{i (1 + i)^n} \right]$$

A = represents a sum of money which is one of a series of equal size ("uniform series") at the end of each period for n periods, the entire series being equivalent to P at interest i.

An interest rate, or discount rate, must be selected for the evaluation. The interest rate frequently used is the estimated cost of borrowing

capital by the entity making the evaluation. (Other factors might also be considered in selecting the interest rate, such as the opportunity cost of capital to the society.)

Since inflation appears to be a permanent part of the economy, adjustment should be made for the fact that future successive payments will be greater by the rate of inflation assumed. Reflecting the difference between the inflation and the discount rate can be modified by substituting i_k for i in the above formula. In the following formula, i_i = discounted interest rate.

$$i_k = \frac{i - k}{1 + k}$$

Where k = inflation rate (both i and k are expressed in decimals).

For the subsequent illustrative examples, the following values will be assumed: i = 8 percent and k = 3 percent (long-term).

$$i_k = .0485$$

A discounted interest rate of .05 will be used.

Selecting An Analysis Period

Selecting an appropriate period of time to use for an analysis is usually not difficult. Even though a facility may have a long useful life, there is a practical limit to the period selected because of the nature of the discounted cash flow analysis. Simply stated, costs occurring well in the future become rather small when discounted compared to costs occurring in the early years of a project life, although escalation must be considered in this context.

Even if a facility has a useful life of 100 years or longer, an analysis period of 40 to 50 years is usually more than adequate, and even shorter periods are generally satisfactory. However, because of the long periods between replacement of some of the items and to illustrate the method, 100 years has been used for some of the examples that follow.

APPLICATION OF METHODOLOGY

The following examples illustrate the application of the present worth costing method and provide order-of-magnitude cost information. The examples relate to cathodic protection system, structural waterproofing systems, and floor finishes. Costs in these examples were obtained from contractors or suppliers for hypothetical installations mid-1976 in the San Francisco Bay Area. For specific installations, cost figures must be based on quantities obtained from preliminary designs and prices that represent the local conditions of the actual project.

Cathodic Protection System

This example compares the installation, maintenance, and replacement costs of two anode spacing alternatives for 10 route miles of cut-and-cover subway construction. Table 6-1, summarizes the costs for the 3,000-foot spacing alternative (see Figure 5-8). The two subtotals show the installation costs for the nine items in the installation and the present worth cost of replacement, operation, and power used over 100 years. The notes in the table explain some of the present worth calculations. The sum of the two subtotals indicates the real cost of the installation on a present worth basis. Table 6-2 gives the same costs for the 200-foot spacing alternative (see Figure 5-8).

Table 6-1

ANODES AT 3,000-FT SPACING

No	Description	Quantity	Unit	Costs	Amount
1	Anodes	360	Ea	167	60,120
2	Rectifiers	18	Ea	1890	34,020
3	Anode junction boxes	18	Ea	790	14,220
4	Cable No. 8	185,400	l.f.	0.37	68,598
	Cable No. 2	180	l.f.	1.74	313
5	Cable trench and conduit	12,600	l.f.	18	226,800
6	Bonding of rebar	660,000	Ea	1.25	825,000
	Carry through units	1,320	Ea	1.25	1,650
7	Vertical condiuts through ground and subway roof	18	Ea	560	10,080
8	Reference electrodes	36	Ea	112	4,032
9	Test stations	36	Ea	204	7,344
	Subtotal				1,252,177
10	Present worth, replacement of anodes				25,000
11	Present worth, all other costs of replacement				113,245
12	Present worth, operation, supervision, etc.				228,252
13	Present worth, operating power				219,122
	Subtotal				585,619
	Total				1,837,796

NOTES: Given an escalation factor of 5%, present worth facotrs and costs are:

Item 10: Replace anodes every 25 years for 100 years, using costs from standard tables.* Present worth every 25 years:

YRS	PW
25	.295
50	.087
75	.026
100	.008
Total	.416

Anode cost = $60,120 x .416 = $25,000 = PW

Item 11: Replace all other construction every 50 years for 100 years, using costs from table. Present worth every 50 years:

YRS	PW
50	.087
100	.008
Total	.095

All other costs = $1,192,057 x .095 = $113,245 PW

Item 12: Operation, supervision etc., 1/4 manyear at a yearly cost of 500 MH @ $23 = $11,500. Using costs from table, present worth of 1 per period of 100 years is 19,848, ∴ PW = $11,500 x 19.848 = $228,252

Item 13: Power requirements, yearly cost is 365 x 24 x 63 x $.02 = $11,040
∴PW = $11,040 x 19.848 = $219,122

*Principles of Engineering Economy, Grant and Ireson

Table 6-2

ANODES AT 200-FT SPACING

No	Description	Quantity	Unit	Unit Costs	Amount
1	Anodes	500	Ea	167	83,500
2	Rectifiers	53	Ea	1,890	100,170
3	Anode junction boxes	53	Ea	790	41,870
4	Cable No. 8	153,120	l.f.	0.37	56,654
	Cable No. 2	530	l.f.	1.24	922
5	Cable trench and conduit	46,640	l.f.	18	839,520
6	Bonding of rebar	660,000	Ea	1.25	825,000
	Carry through units	1,320	Ea	1.25	1,650
7	Vertical conduits through ground and subway roof	53	Ea	560	29,680
8	Reference electrodes	106	Ea	112	11,872
9	Test stations	106	Ea	204	21,624
	Subtotal				2,012,462
10	Present worth, replacement of anodes				34,770
11	Present worth, all other costs of replacement				183,250
12	Present worth, operation, supervision, etc.				228,250
13	Present worth, operating power				219,120
	Subtotal				665,390
	Total				2,677,852

NOTES: Given an escalation factor of 5%, present worth costs and factors are:

Item 10: Replace anodes every 25 years for 100 years (use same factor shown in Table 6-1) ∴ PW of anodes is 83,500 x .416 = $34,770

Item 11: Replace all other construction every 50 years for 100 years (use same factor shown in Table 6-1) ∴ PW of other costs is 1,928,962 x .095 = $188,250

Item 12: Present worth same as item 12 in Table 6-1 or $228,250

Item 13: Present worth same as Item 13 in Table 6-1 or $219,120

A comparison of the total costs in the two tables shows that the 3,000-ft anode spacing appears more economical, both in first and subsequent costs. Although, given the normal physical constraints in any urban area, the spacing would probably have to be varied along the route because of physical obstructions, the calculations show the desirability, where possible, of adopting the greater anode spacing.

Waterproofing Systems (and Cathodic Protection)

The importance of selecting the correct waterproofing system for the groundwater conditions encountered was discussed in Section 5. To indicate the magnitude of costs for waterproofing systems, installation costs have been estimated for typical cut-and-cover and tunneled structures (Figure 5-3), and incremental costs have been estimated for two waterproofing systems, one partial and one complete. The cost of providing cathodic protection to the partial waterproofing alternative has also been included.

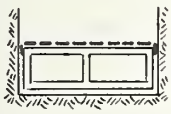
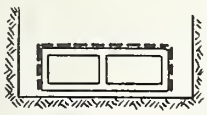
The present worth costing method has been used in assessing the real cost of these systems.

Pricing of Alternatives. The cost of a typical cut-and-cover twin cell structure was derived from costs given for the model cut-and-cover line structure in Section 7 (Systems Analysis of Rapid Transit Underground Construction Report DOT/TSC-75-72, I & II. The quantities were prorated from the model structure length (of 3,225 feet) to 5,280 feet (1 mile), and the model cost was escalated to mid-1976 prices.

The waterproofing system alternatives were: System 1, 3 ply, and System 2, 3 ply-Construction Method 2, as priced in Table 6-3. The cathodic protection system costs were derived from the average of the two spacing alternatives previously discussed.

TABLE 6-3

WATERPROOFING MEMBRANE COSTS

SYSTEM OF COVERAGE	TYPE OF MEMBRANE	1 Mile (5280') TRACKWAY COST	1 Station 838' Long STATION COST
		SYSTEM - 1	
Roof Coverage Only. 	Hypalon	615,300	322,100
	Poly/Butyl	336,700	106,000
	3 Ply	423,900	134,800
	Bentonite	262,800	79,200
		SYSTEM - 2 Construction Method 1	
Complete Coverage. Membrane Applied Directly to Walls.	Hypalon	2,912,200	774,000
	Poly/Butyl	2,164,700	537,600
	3P-R&W, 5P-F	2,457,100	633,900
	Bentonite		
		SYSTEM - 2 Construction Method 2	
Complete Coverage. Wall Membrane Applied to Sheeting	Hypalon	1,732,400	557,000
	Poly/Butyl	958,800	300,700
	3P-R&W,5P-F	1,278,100	396,900
	Bentonite	780,777	
		SYSTEM - 3 Construction Method 1	
Roof/Wall Coverage. Membrane Applied Directly to Walls. 	Hypalon	2,433,583	596,800
	Poly/Butyl	1,906,000	444,000
	3 Ply	2,059,900	570,100
	Bentonite	1,535,000	417,300
		SYSTEM - 3 Construction Method 2	
Roof/Wall Coverage. Wall Membrane Applied to Sheeting.	Hypalon	1,243,800	359,800
	Poly/Butyl	727,100	203,000
	3 Ply	881,000	253,100
	Bentonite	653,200	180,300

The cost estimates for the tunneled structures are given in Table 6-4. The basic information was derived from both DOT/TST 75-72-11 and DOT/TST 75-72-102. The latter was modified to obtain the costs for a 3,000-foot tunnel system with 7-inch thick solid precast concrete segmented linings. For System 1 waterproofing, the segments were assumed to be gasketed on the four faces and the erected lining was assumed to be caulked. For System 2 waterproofing, allowance was made for the increase in diameter of the precast outer lining, the caulking was omitted, and sprayed polyurethane liquid membrane and a 6-inch inner lining were included. The total costs of the two waterproofing systems were then prorated from 3,000 feet to 5,260 feet (1 mile). These costs are shown in Figure 6-1 as increments to the base costs of the cut-and-cover and tunneled structures.

Installation Cost/Function Appraisal of the Alternatives. The following discussion is applicable to both the cut-and-cover and tunneled structures.

As the detailed discussion in Section 4 indicates, the seepage of groundwater into subway structures may become a continuous maintenance cost, both for structures and for many items within the structures. As Figure 6-1 shows, the degree of protection provided has an appreciable impact on the installation costs, particularly for tunnels. For the cut-and-cover System 1 waterproofing (which is recommended for almost all ground conditions), the cost of the structure is increased by 1.76 percent or $424,000 per mile. With complete System 2 waterproofing, the percentage increase is 5.31 or $1,278,000 per mile.

However, when compared with System 1, where the roof waterproofing should be provided in any case, the differential increment is only 3.55 percent or $854,000 per mile. On the other hand, for tunneled constructions, the increased construction costs for the provision of an inner membrane produces a major cost increment on the base system (assumed

TABLE 6-4

COST COMPARISON OF SINGLE LINED TUNNEL

VS SECONDARY LINED TUNNEL

WORK EVENT	UNIT	3000 FT EA SINGLE LINED TUNNEL - 7' PC LINER - 16'6" ID UNIT COST $/SYSTEM FT	TOTAL AMT	LINED TUNNEL - PC LINER + 6" LINING UNIT COST $/SYSTEM FT	TOTAL AMT
TUNNEL DRIVING COSTS					
LINER ERECTION & CAULKING	LF	370		300	
GROUTING	LF	300	1740	300	1730
TUNNEL LINER	LF	1070	5,220,000	1130	5,190,000
EXCAVATION	LF	2530	7,590,000	2830	8,490,000
DISPOSAL	LF	100	300,000	110	330,000
CONCRETE CONSTRUCTION					
INVERT & WALKWAY	LF	210	630,000	210	630,000
POLYURETHANE LIQUID MEMBRANE	LF			170	510,000
6" CAST IN PLACE LINING	LF			120	360,000
REINFORCING FOR CIP LINING	LF			40	120,000
SUB TOTAL	LF	4580	13,740,000	5210	15,630,000
COST OF SHAFT, MOB & CW DRAIN			2,002,000		2,002,000
TOTAL		5687	17,062,000	5877	17,632,000
BASE COST 1 SYSTEM MILE		1,574,200 x 1.753 =	27,595,720	17,763,200 x 1.753 =	30,908,890

* ALL COSTS ARE AS OF JULY 1976

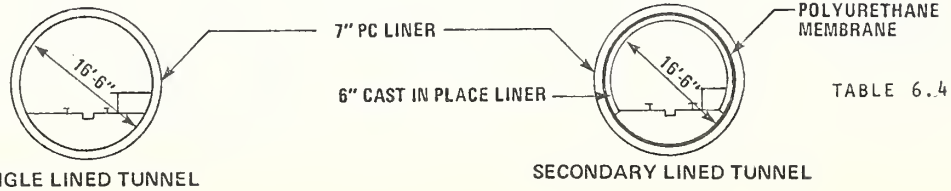
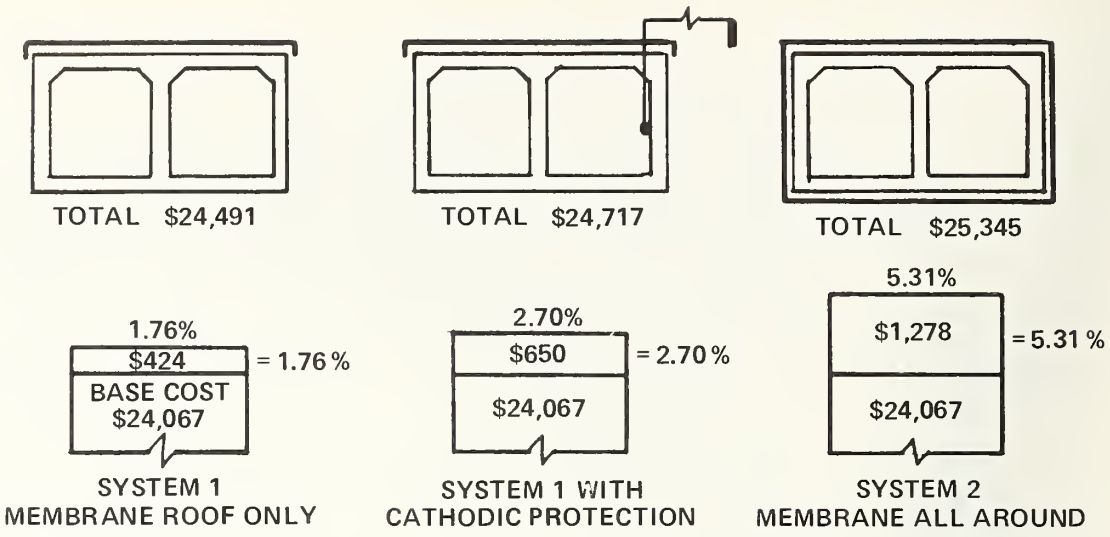
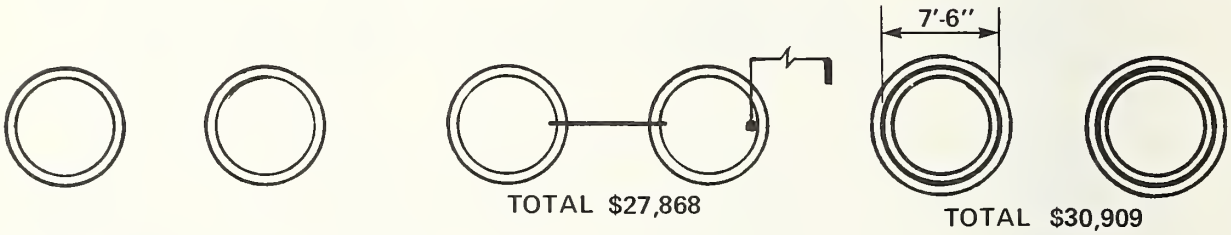
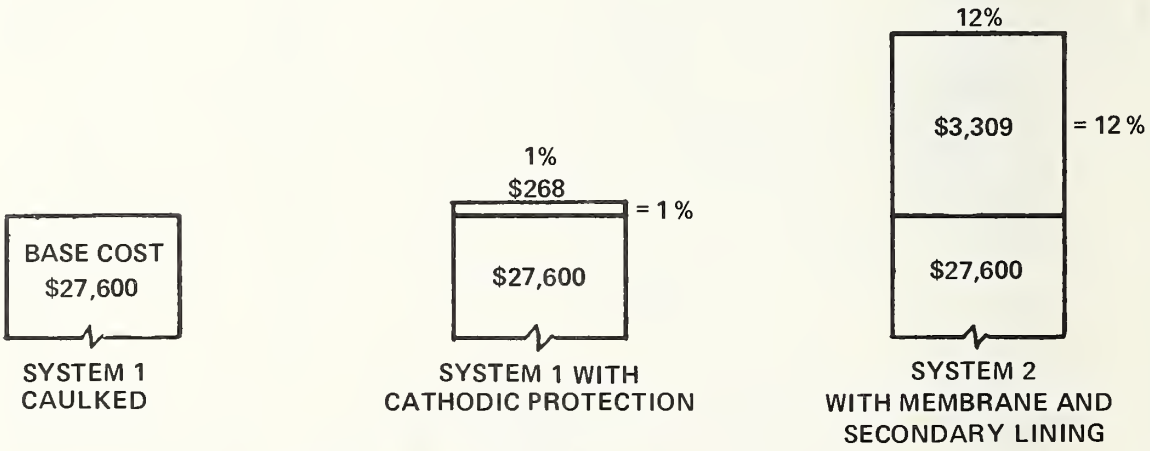


TABLE 6.4



CUT & COVER SECTIONS





CONCRETE TUNNELS

Note: Costs are $1,000 per mile.

Figure 6-1. BASE STRUCTURE COST WITH INCREMENTAL COSTS FOR CATHODIC PROTECTION AND ALTERNATIVE WATERPROOFING SYSTEMS

caulked). These incremental costs are 12 percent or $3,309,000 per system mile. (In actual fact, the differential may even be greater if an effective segment gasket is employed in System 1 and the amount of caulking is reduced).

Cathodic protection has been used in conjunction with System 1 waterproofing on the assumption that under certain conditions stray currents from the train dc power system will be transmitted to and through the structure via water seepage or dampness in the concrete. In addition, stray currents from external sources may be carried into the structure in the same manner. Conversely, the complete membrane in System 2 will, to all intents and purposes, prevent the passage of stray currents. It will be noted that the incremental cost, which includes present worth cost of maintenance of the cathodic protection, is a relatively modest $226,000 for the cut-and-cover structure ($268,000 for the tunnels) amounting to about 1 percent of the System 1, or base costs.

Real Cost Evaluation of Alternative Systems. A certain degree of "crystal ball gazing" is required to assess the impact of water in subway structures upon short term and long term costs, due to the complex factors involved.

To compare differences in function, System 2, with its complete membrane, will in one degree or another reduce the following maintenance cost items:

1. Energy; pump and drainage maintenance,
2. Cathodic protection or monitoring; attack from stray currents and consequent damage,
3. Maintenance and replacement of trackway (wayside equipment, metallic items, such as light fixtures, conduits, miscellaneous metal, etc.),
4. Maintenance and repair of the structure, and
5. Maintenance of installed mechanical and electrical equipment with station (escalator and elevator rooms, lights, etc.) and architectural finishes.

Illustrative Example. When analyzing the cost benefits between System 1 waterproofing on roof only and System 2 waterproofing all around for a 1-mile cut-and-cover track structure, the following are assumed:

The structure is in variable soils with a fairly high groundwater table, perhaps 10 to 15 feet above the roof

A certain amount of cracking will occur in the concrete and, in System 1, will admit 0.01 gpm per system foot

One pump station is located in each system mile with two 500 gpm pumps for System 1

The same number of sumps and pumps will be required for emergencies in System 2 but the pump size will be 250 gpm and the sumps will be 25 percent smaller

The following costs have been estimated from the somewhat limited information furnished by the transit properties.

Item 1 — Maintenance of 1 Pump Location	$/yr
Inspection and maintenance	3,300
Power: (16 x 52) hr/yr (15 hp, 12 kWh) @ 13 mil	130
Biannual pump sump cleaning: 4 men, 2 days @ $120/day	960
Total per pump station	$4,390

Item 2 — Maintenance and Repair of 1 Mile Structure (including painting and drainage:)	
Inspector and one five-man gang, 12 days/yr Labor ($120 x 6) x 12	8,640
Equipment and tools	2,760
Material	1,200
	$12,600

Item 3 — Replacement Items. In a wet, underground trackway, some of the installed equipment, such as lights, conduits, wayside equipment, and some of the track components may have to be replaced frequently. For the calculations, it is assumed that light fixtures, conduits, and like items of $50,000 per mile in value will have to be replaced every 30 years.

For the economic comparison of the two systems, it is assumed for System 2 that 20 percent of the cost of Items 1, 2, and 3 will be required; therefore, 80 percent of the costs estimated will be used in the present worth comparative evaluation Table 6-5.

Table 6-5

PRESENT WORTH COMPARISON

Item	Cost ($)
System 1	
Base cost plus roof membrane	24,491,000
Present worth value:	
Item 1 (Pumps and sumps) 3,390 x .8 x 19.85 (from PW tables 100 yr)	54,000
Item 2 (Maintenance and repair of structure) 12,600 x 0.8 x 19.85	200,000
Item 3 (Replacement — 30 yr basis) (50,000 x .8) [(15.4 x 0.23) + (18.9 x 0.054) + (19.8 x .0124)] = 40,000 x (3.54 + 1.02 + .25)	192,000
	24,937,000
Cathodic protection, if required	226,000
Total	25,163,000
System 2	
Base cost plus membrane all around	25,345,000

With the assumed values of the three items, even without cathodic protection, the cost difference between the two systems is small. Other items not debited against System 1 might include track maintenance and trackway cleaning, as well as unknown effects of a transit properties cathodic protection system upon other agencies' protection systems. These items might well make System 2 economically more favorable.

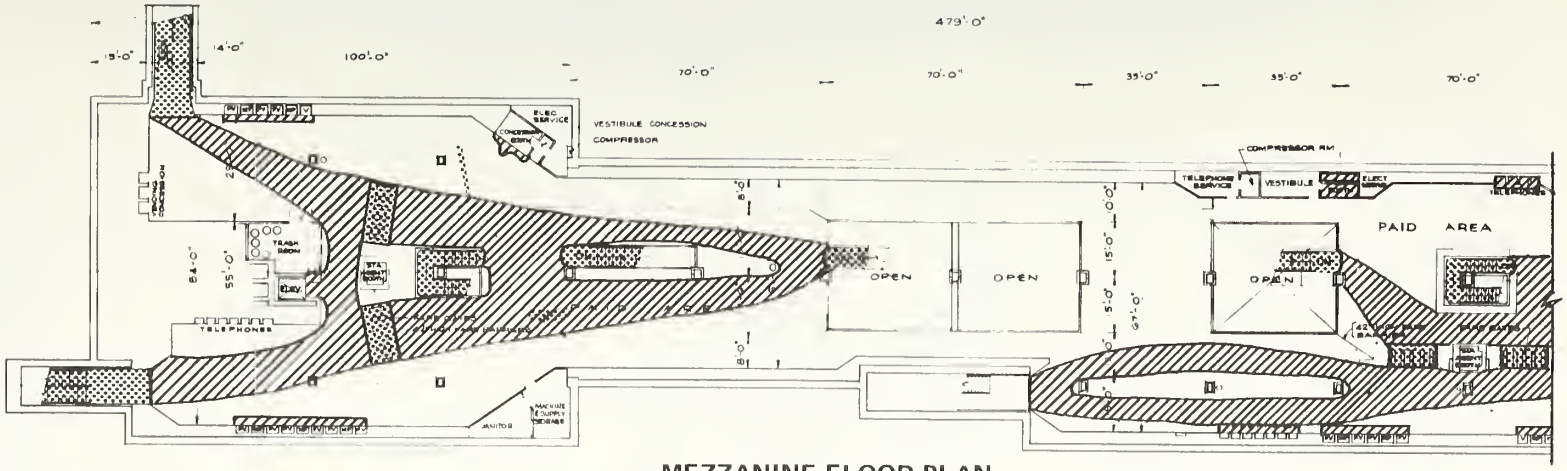
Floor Finishes

As noted in the preceding sections, maintenance of floor finishes is a matter of serious concern to the majority of transit maintenance engineers. The reasons for this concern may be summarized as follows:

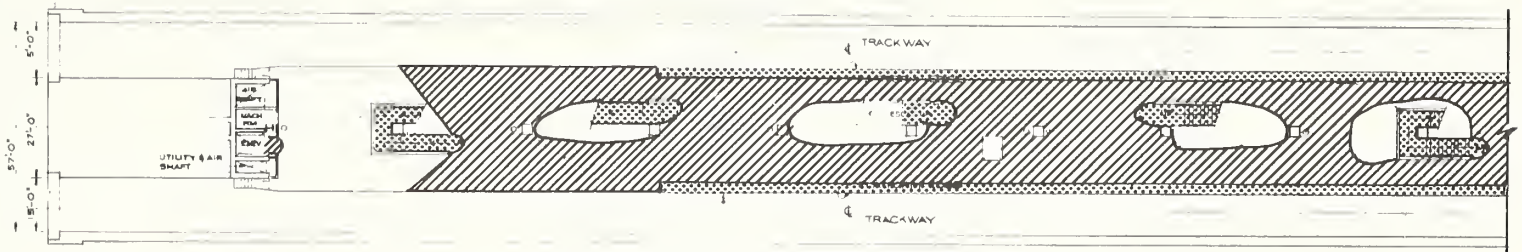
> Wear and cleaning characteristics vary widely in the several different floor finishes used in subway stations,
>
> Intensity of wear upon the finish varies considerably among different locations in a station, and
>
> Floor cleaning is the single largest cost item in the janitorial budget — which in turn is generally the largest item in a rapid transit station's total annual structural maintenance budget.

Selecting floor finishes that will result in the lowest cost over the life of a rapid transit station is a complex process because it is a function of the differences in the original installation costs, annual cleaning costs, annual repair costs, and the length of time required before replacement is necessary. The discounted cash flow analysis method can readily perform the analysis required to determine the lowest cost solution as exemplified below, but the obvious warning that must be given is that the results are only as good as the values assumed for the variables.

Station Floor Areas. The layout of a typical subway station, as indicated in Figure 6-2, was used as a base for estimating quantities of floor finishes needed and determining wear characteristics. It was assumed that 14,000 patrons would pass through the station on an average day and that floor finishes in the areas indicated would wear at different rates according to the density of the traffic. Heavy wear was given a value of 100, medium wear 50, and light wear 10. Table 6-6 shows the floor area for a typical subway station by rates of wear.



MEZZANINE FLOOR PLAN



UPPER PLATFORM LEVEL FLOOR PLAN

SECTION

HEAVY WEAR MEDIUM WEAR LIGHT WEAR

Figure 6-2. SUBWAY STATION FLOOR WEAR AREAS

The major variables selected were four types of floor coverings, two extreme climatic conditions, and two types of design that would affect the ease of cleaning. Thus, there are 16 potential alternatives to analyze. These are shown below:

Floor Coverings

Quarry tile (4 in. x 8 in.),

Terrazzo, dark (2 ft. x 2 ft.),

Rubber tile (Pirelli 40 in. x 40 in. x 9/32 in.), and

Carpet, airport type*.

Climate

Dry climate such as California or Florida,

Wet climate such as Chicago or Toronto.

Design or Obstruction Level for Cleaning

Design is maximized for easy maintenance; for example, columns, trash cans, benches, corners, restroom details, and barriers are designed and located to provide minimum obstruction to the cleaning operation,

Other design criteria override easy maintenance criteria.

---

*Although carpet was not installed in stations in any of the properties visited, at more than one property interest was expressed.

Table 6-6

SUBWAY STATION FLOOR AREA AND WEAR RATES

Area	Sq Ft	% of Total Area
Mezzanine		
General floor area (600 ft x 60 ft)		
Heavy wear	3,600	10
Medium wear	14,400	40
Light wear	18,000	50
Total	36,000	100
Other areas (a) (100 ft x 10 ft)		
Heavy wear	1,000	100
Platform (600 ft x 30 ft)		
Heavy wear	2,700	15
Medium wear	12,600	70
Light wear	2,700	15
Total	18,000	100
Total Station		
Heavy wear	7,300	13
Medium wear	27,000	49
Light wear	20,700	38
Total	55,000	100

(a) Staff room, vestibule, toilets, custodial

Table 6-8 contains the calculations of the present worth of the replacement costs for each type of floor covering under dry climatic conditions. This table also shows the combined total of the original cost and the present worth cost of replacement.

Table 6-7 shows the estimated annual maintenance and repair costs under dry climatic conditions and the present worth of these costs for the 80-year period used in the analysis. The assumptions used in estimating maintenance and repair costs are shown in Appendix 6.1.

Table 6-9 contains an example of the present worth of the total costs: original, replacement, maintenance, and repairs for one type of floor covering (quarry tile) under dry climatic conditions and with few obstructions to maintenance.

Similar calculations were mad for each type of floor covering, for two climatic conditions, and for two design variables; the resulting present worth costs are tabulated in Table 6-10 and in index form in Table 6-11, using quarry tile Alternate 1 as a base.

Table 6-7

PRESENT VALUE OF ANNUAL MAINTENANCE AND REPAIR COSTS - DRY CLIMATE

	Ceramic Tile	Terrazzo	Rubber Tile	Carpet
Obstruction Level I				
Maintenance	$ 745,800	$ 745,800	$ 745,800	$ 875,000
Repair	4,700	15,400	18,100	39,500
Total	750,500	761,200	763,900	914,500
Obstruction Level II				
Maintenance	1,113,500	1,113,500	1,113,500	1,194,700
Repair	5,600	18,500	21,700	47,400
Total	1,119,100	1,132,000	1,135,200	1,242,100

Table 6-8

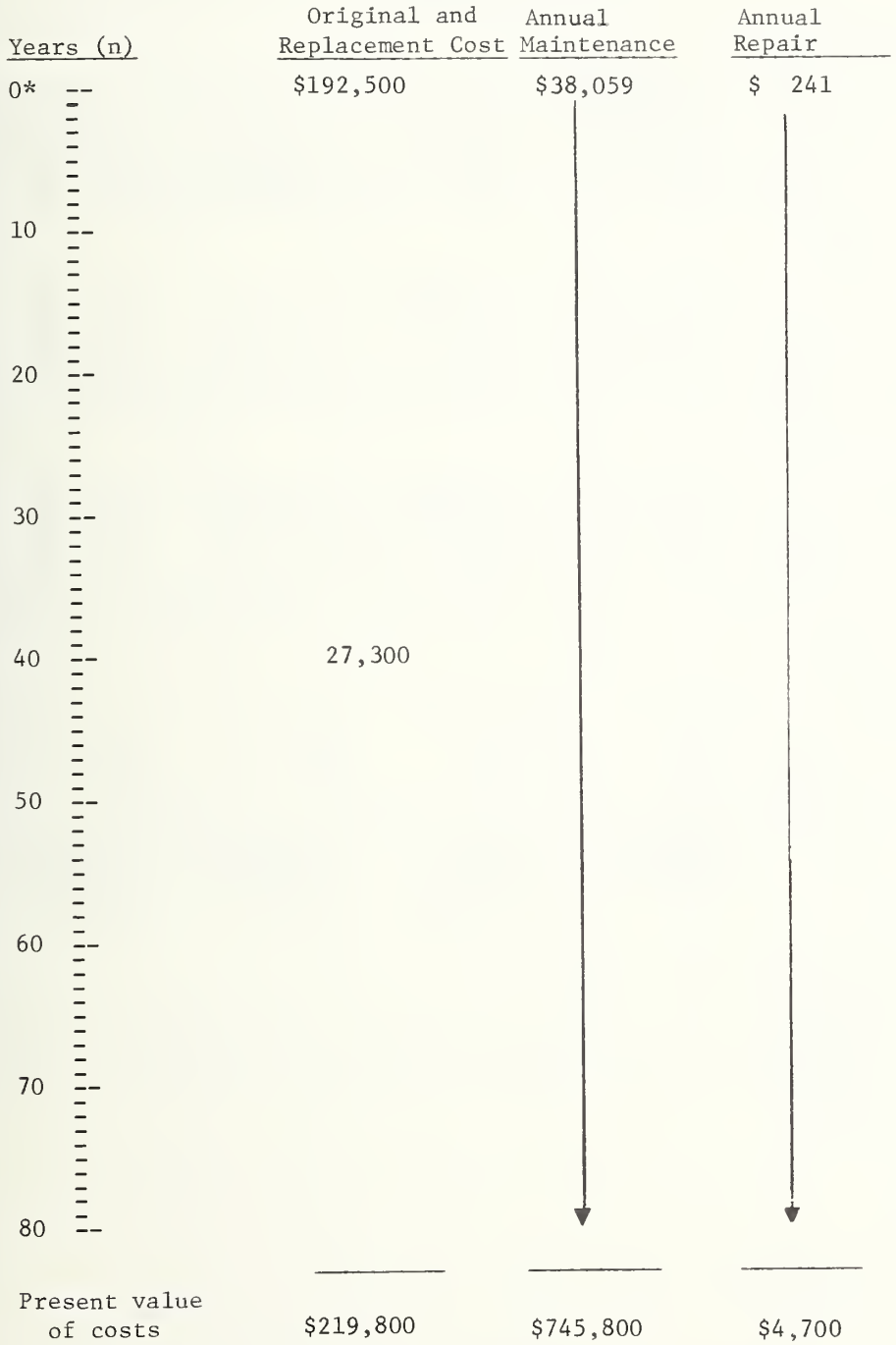
PRESENT WORTH OF ORIGINAL AND REPLACEMENT COSTS - DRY CLIMATE
(5 Percent Discount Rate)

Years (n)	Ceramic Tile	Terrazzo	Rubber Tile	Carpet
0[(a)]	192,500	236,500	264,000	121,000
				90,300
10				67,400
				50,300
20			99,500	
				37,500
30		54,700		28,000
				20,900
40	27,300		37,500	
				15,600
				11,600
50				
				8,700
60		12,700	14,100	6,500
				4,800
70				
				3,600
				2,700
80				
Present value of replacement costs	27,300	67,400	151,100	347,900
Total: Original and PV of Replacement Costs	219,800	303,900	315,100	468,900

(a) Original Costs

Table 6-9

QUARRY TILE - PRESENT WORTH OF ORIGINAL, REPLACEMENT AND ANNUAL MAINTENANCE AND REPAIR COSTS IN DRY CLIMATE CONDITIONS
(5 Percent Discount Rate)



Present value: All costs = $970,300

Table 6-10

PRESENT WORTH COST SUMMARY

($)

Climate	Obstruction Level	Cost Item	Ceramic Tile	Terrazzo	Rubber Tile	Carpet
Dry	I	Installation	192,500	236,500	264,000	121,000
		Replacement	27,300	67,400	151,100	347,900
		Clean	745,800	745,800	745,800	875,000
		Repair	4,700	15,400	18,100	39,500
		Total	970,300	1,065,100	1,179,000	1,383,400
Dry	II	Installation	192,500	236,500	264,000	121,000
		Replacement	27,300	67,400	151,100	347,900
		Clean	1,113,500	1,113,500	1,113,500	1,194,700
		Repair	5,600	18,500	21,700	47,400
		Total	1,338,900	1,435,900	1,550,300	1,711,000
Wet	I	Installation	192,500	236,500	264,000	121,000
		Replacement	41,200	88,700	238,400	750,500
		Clean	895,000	895,000	895,000	1,312,500
		Repair	5,400	18,500	24,100	79,000
		Total	1,134,100	1,238,700	1,421,500	2,263,000
Wet	II	Installation	192,500	236,500	264,000	121,000
		Replacement	41,200	88,700	238,400	750,500
		Clean	1,336,200	1,336,200	1,336,200	1,792,000
		Repair	6,500	22,200	28,900	94,800
		Total	1,576,400	1,683,600	1,876,500	2,758,300

Table 6-11

COST COMPARISON FOR VARIOUS ALTERNATIVES
(Index)

Alternative No.	Floor Type	Climate	Obstruction Level	Floor %			
				Dry		Wet	
				I	II	I	II
1	Ceramic Tile	Dry	I	100			
2			II		138		
3		Wet	I			117	
4			II				162
5	Terrazzo	Dry	I	110			
6			II		148		
7		Wet	I			128	
8			II				173
9	Rubber Tile	Dry	I	122			
10			II		160		
11		Wet	I			146	
12			II				192
13	Carpet	Dry	I	143			
14			II		176		
15		Wet	I			233	
16			II				284

Index: Quarry tile in dry climate with obstruction level I = 100

7 MAINTENANCE ORGANIZATIONS AND PROCEDURES

Detailed information about the composition of the maintenance organizations and their actual relationships to the operations organizations was often difficult to obtain from many of the properties visited. A part of this problem arose from the fact that some of the maintenance acticities of many of the properties surveyed were undertaken by entities other than the ones interviewed, and time did not permit making the necessary contacts with those responsible for the actual maintenance. The numerous physical variables in each property presented another difficulty which grossly affected the requirements for maintenance of some of the items and, consequently, the size and composition of the organization. Figure 7-1 categorizes the three main groups of variables under "Labor and Schedule," "Fundamentals," and "Design and Geology." Each one in the second two groups affects the degree of maintenance of most, or all, of the maintainable items under "Trackway and Components" and "Station" and, consequently, the size and composition of the two maintenance organizations of "Maintenance and Repair" and "Cleaning." The "Labor and Schedules" variable items principally affect the two maintenance organizations only.

In general, however, similar maintenance tasks were assomplished at all the properties visited, and task flow charts could be established for comparative purposes more readily than could personnel manning charts.

Meaningful costs of undertaking various kinds of maintenance in terms of labor, materials, equipment, overhead, etc., were not available from any of the properties for maintenance of subway-related items only,

because most of the activities cover the counterparts in the surface facilities. However, in some cases, labor and equipment data were provided for individual items.

DATA RECEIVED

Where the information was obtainable, task organization flow charts have been compiled and are displayed in Figures 7-2 through 7-13. The principal subway-related tasks that have been identified are indicated by shading. The highlights of each organization are briefly discussed in the following paragraphs.

London

Figure 7-2 indicates the several general operating and engineering functions. Under the direction of "Engineering," the task headings "Civil," "Mechanical," and "Signals" appear with their respective maintenance responsibilities indicated. It will be noted that Ventilation is organized under New Work, and (subway) Structures and Subway Finishes are the immediate responsibility of Works and Buildings.

Paris

The maintenance engineering of this property is based on the major portion of the onsite structure maintenance being undertaken by outside contractors. The engineering organization responsibilities, therefore, are largely oriented towards inspection and supervision of the contractors who undertake the cleaning, repair, and replacement of the items within the subway complex. Emergency repairs, however, are undertaken by owner mobile maintenance task forces operating from regional workshops.

Figure 7-3 shows the three major engineering groups involved, Buildings, Subways (and related Surface Structures), and Infrastructures (Tunnels and Bridges). The task responsibilities of the three groups are indicated,

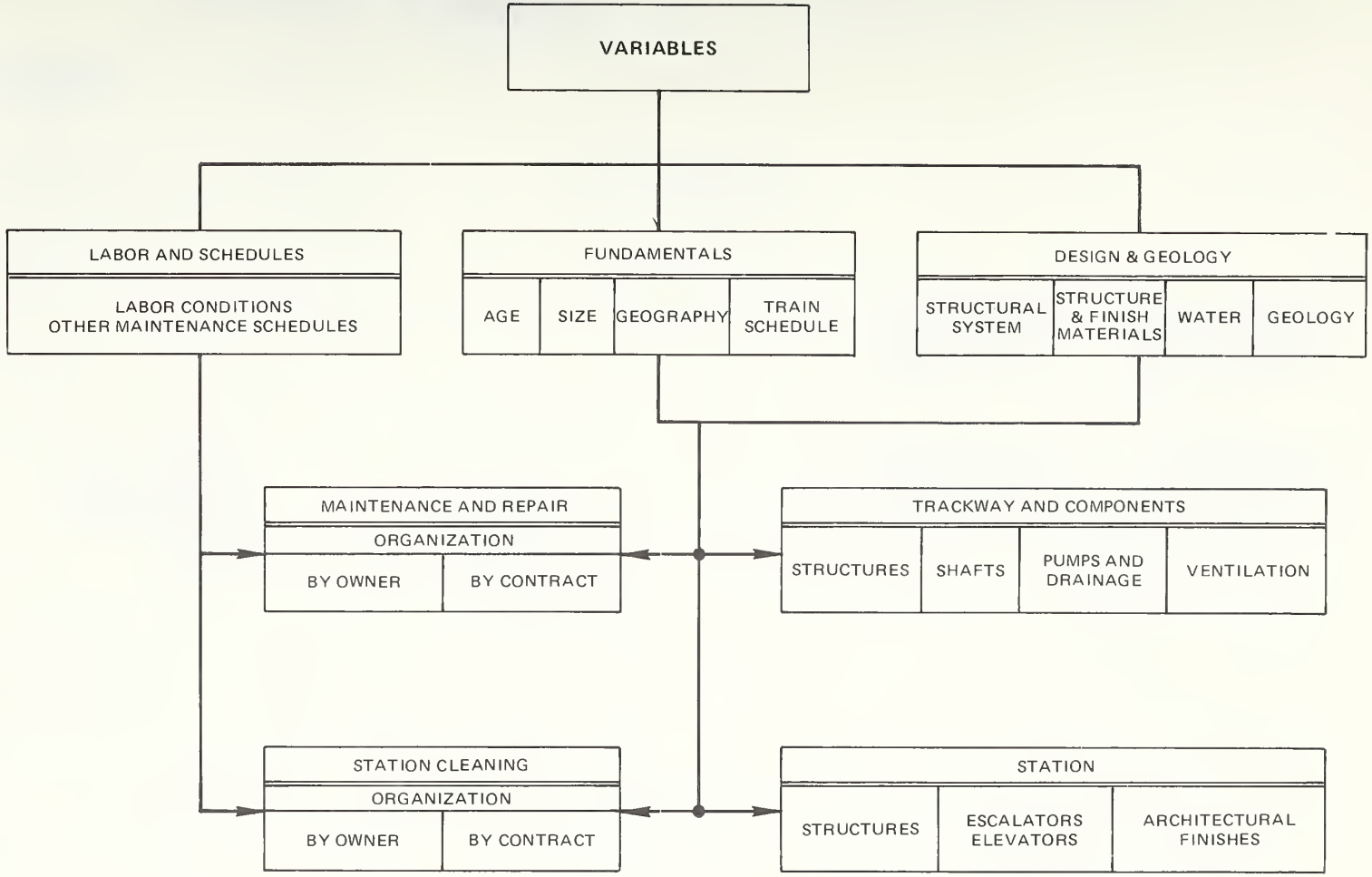


Figure 7-1. INTERACTION OF VARIABLES ON MAINTENANCE ORGANIZATIONS AND MAINTAINABLE ITEMS

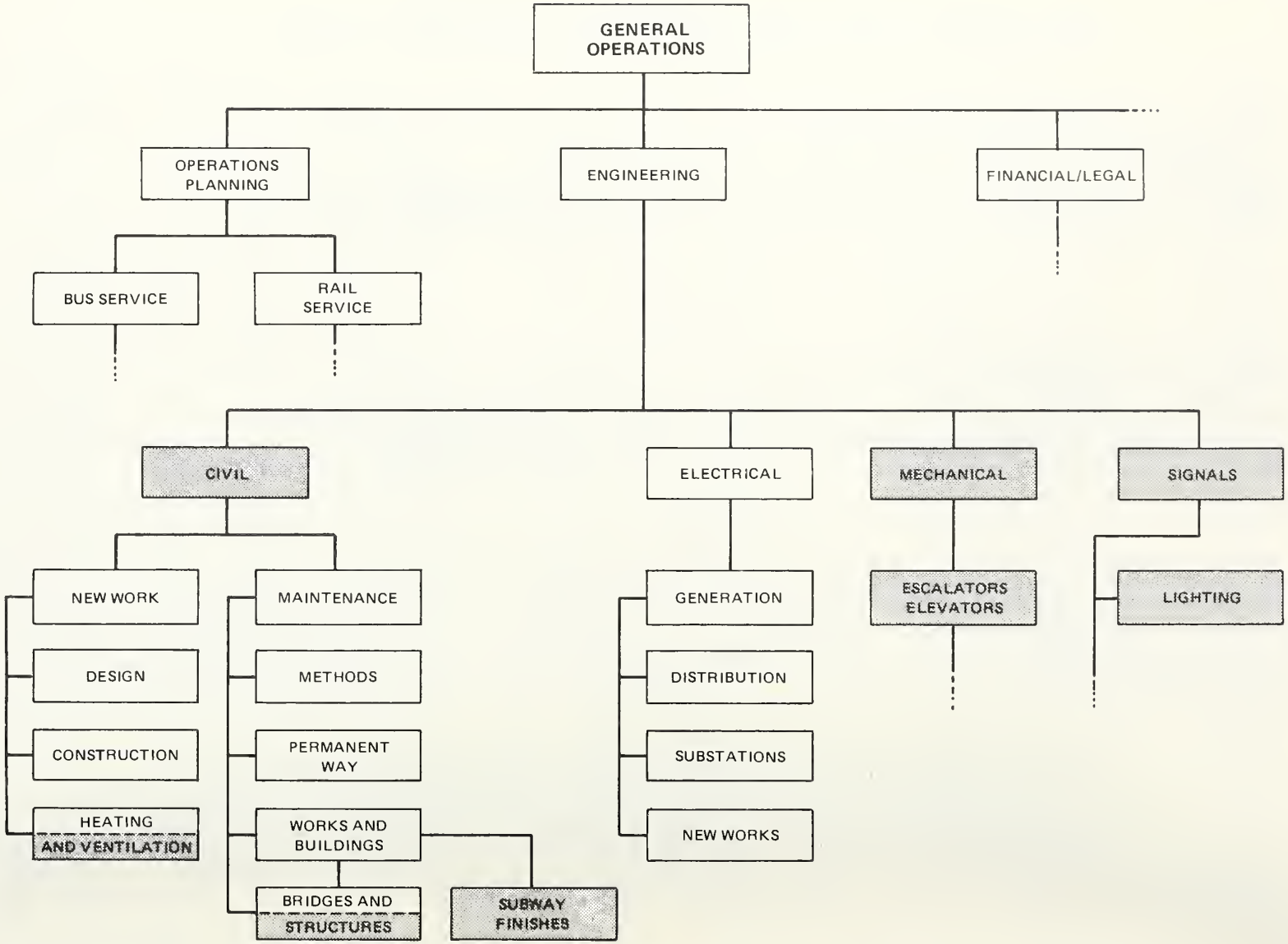


Figure 7-2. LONDON

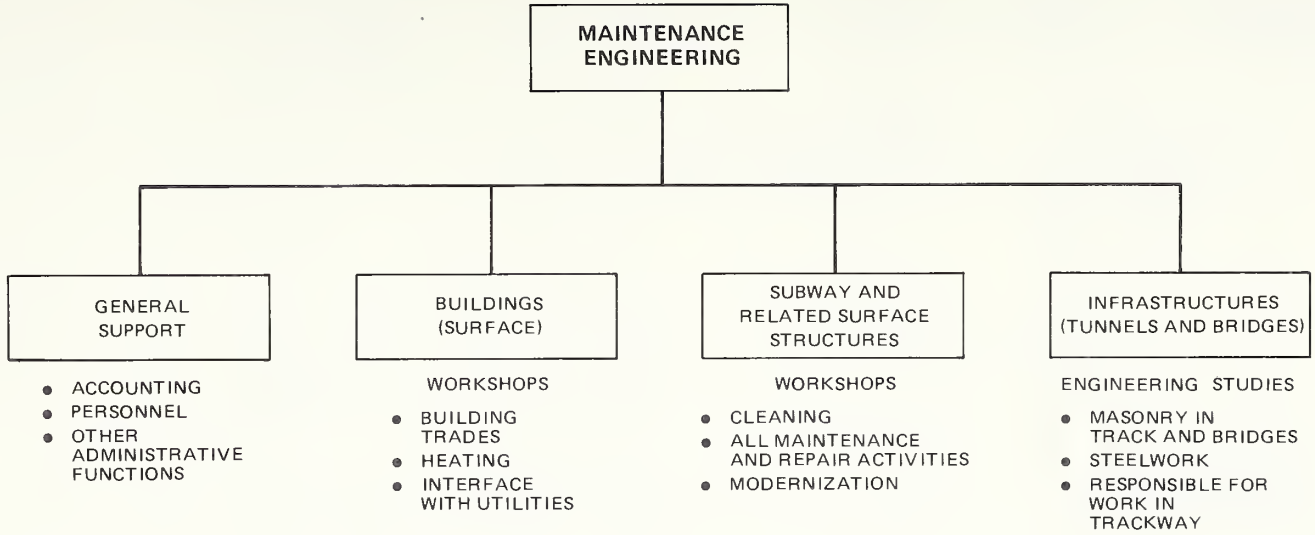


Figure 7-3. PARIS

the last two being concerned with most of the work required to maintain the underground structures.

Stockholm

The two groups jointly responsible for various aspects of new work and maintenance are the City Street Department and the AB Storestockholms Localtrafik (SL). The responsibilities assigned are indicated in Figure 7-4.

Of particular interest is the fact that the Street Department undertakes the maintenance of the subway rock tunnels while Localtrafik maintains the other structures.

Brussels

The Brussels Municipal Transportation Authority, S.T.I.B., operates the system and in 1960 established a special department to plan and to construct the system in stages. At the time of the visit, street cars were providing transit service through the structures.

Because the system is new, maintenance, other than of mechanical equipment and cleaning was not a significant item, and specific maintenance task information was not obtained. Cleaning was undertaken by especially trained contract labor and directly supervised by the Transportation Authority.

Hamburg

Three entities are responsible for planning, design and construction, and operation and maintenance respectively. These are the consulting firm G.V.V. (a wholly owned subsidiary of the transportation authority), the City of Hamburg (Public Works Department), and the City Transportation Corporation HHA. Figure 7-5 shows the responsibilities of these three

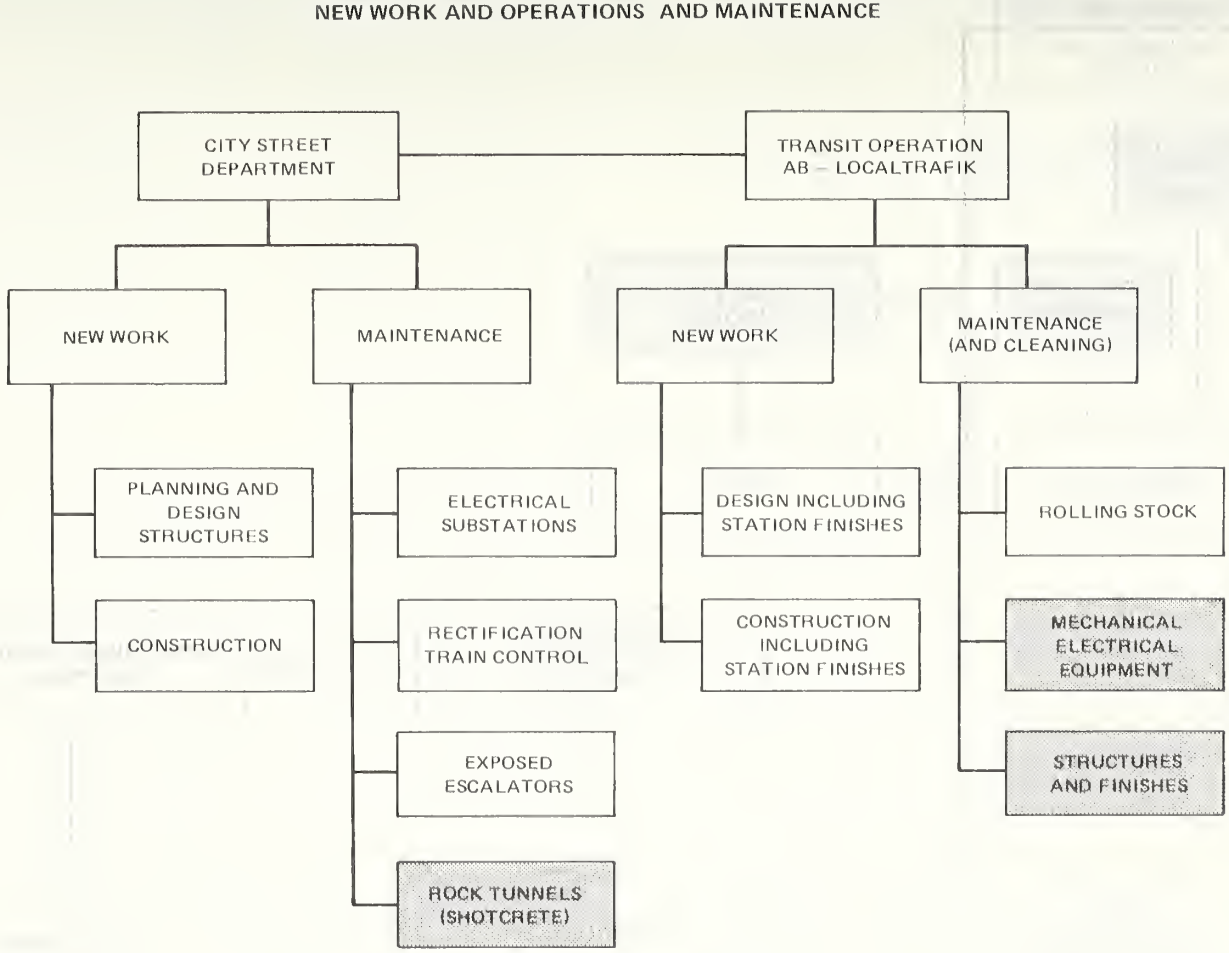


Figure 7-4. STOCKHOLM

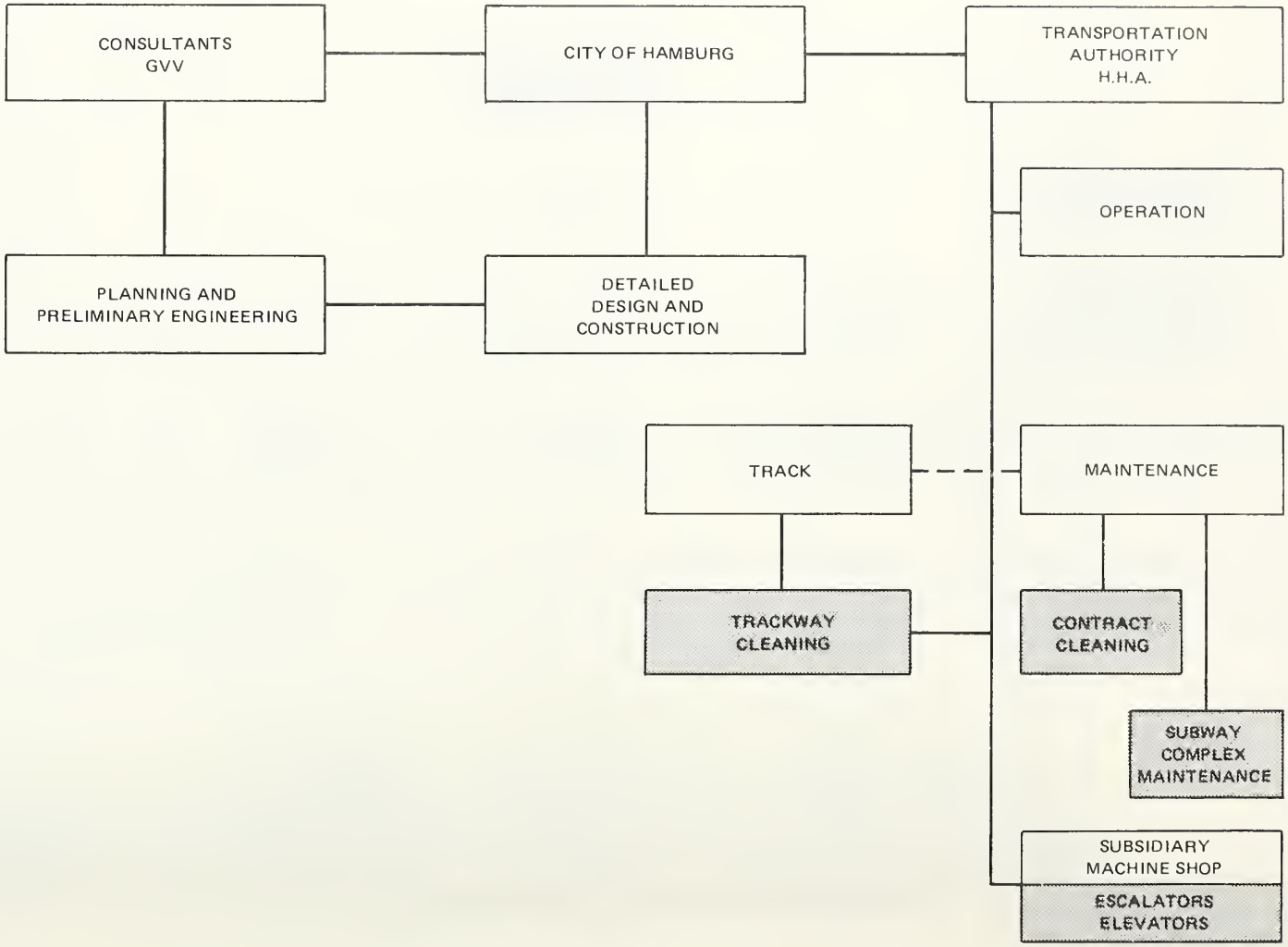


Figure 7-5. HAMBURG

groups as well as some details of the maintenance task organizations. The figures shows that "trackway cleaning" is a Track Maintenance responsibility, the stations cleaning is contracted, and a subsidiary machine shop maintains the escalators and elevators.

Berlin

The responsibilities of planning, design and construction, and operation and maintenance are given to three entitites. These are Berlin Traffic and Transportation Consultant (BVC), City of Berlin (Public Works), and Berlin Traffic Authority (BVG), respectively. The responsibilities assigned to all are shown in Figure 7-6; an organization of detailed tasks was not available.

Munich

Planning, design, and construction are undertaken by the City of Munich, Department for Subway Construction (SV). The system is operated and maintained by the Municipal Utility and Transportation Department. Figure 7-7 indicates this arrangement with a partial task responsibility flow chart. "Escalator Maintenance" will be changed from "Contract" to "Owner", when the initial 5-year post-installation period is complete.

Toronto

Subway maintenance is the responsibility of the Plant Department. Figure 7-8, which indicates those portions of the ogranization that relate to the maintenance of the subway complex, shows that this is a responsibility shared among the three groups of "Track," "Electrical," and "Structures." "Track" is responsible for operating the work trains to serve the other two groups for work within the trackway as well as for cleaning the trackway. "New Construction" is undertaken by a separate entity (not indicated) called Engineering and Subway Construction.

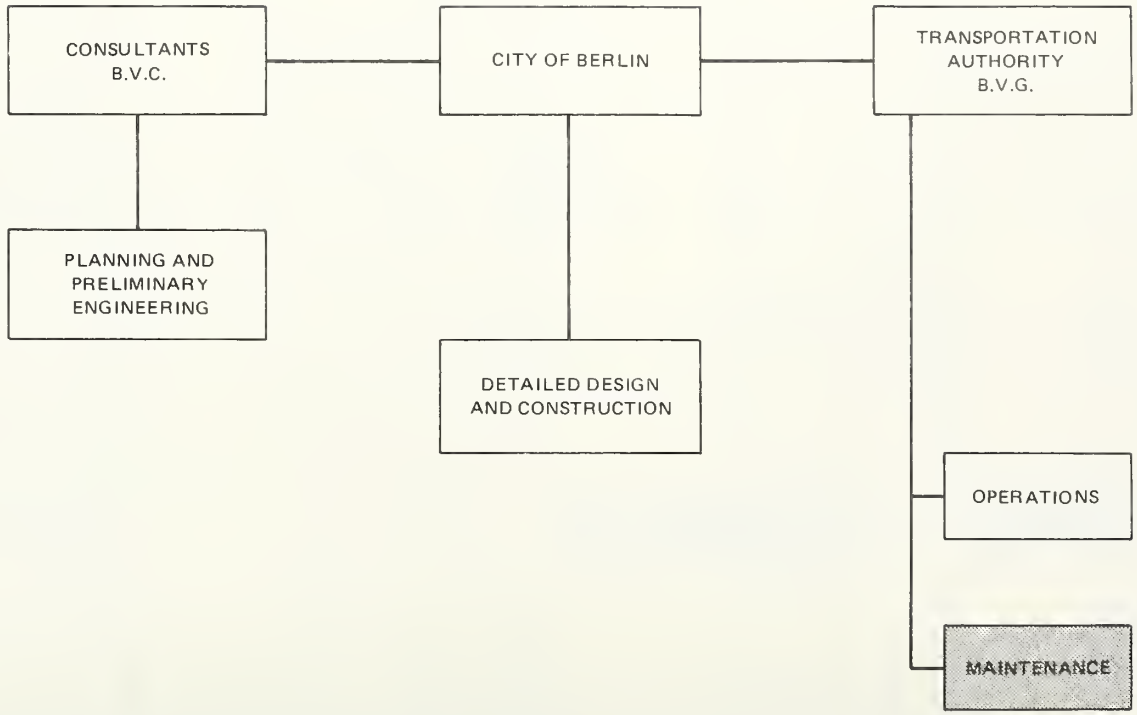


Figure 7-6. BERLIN

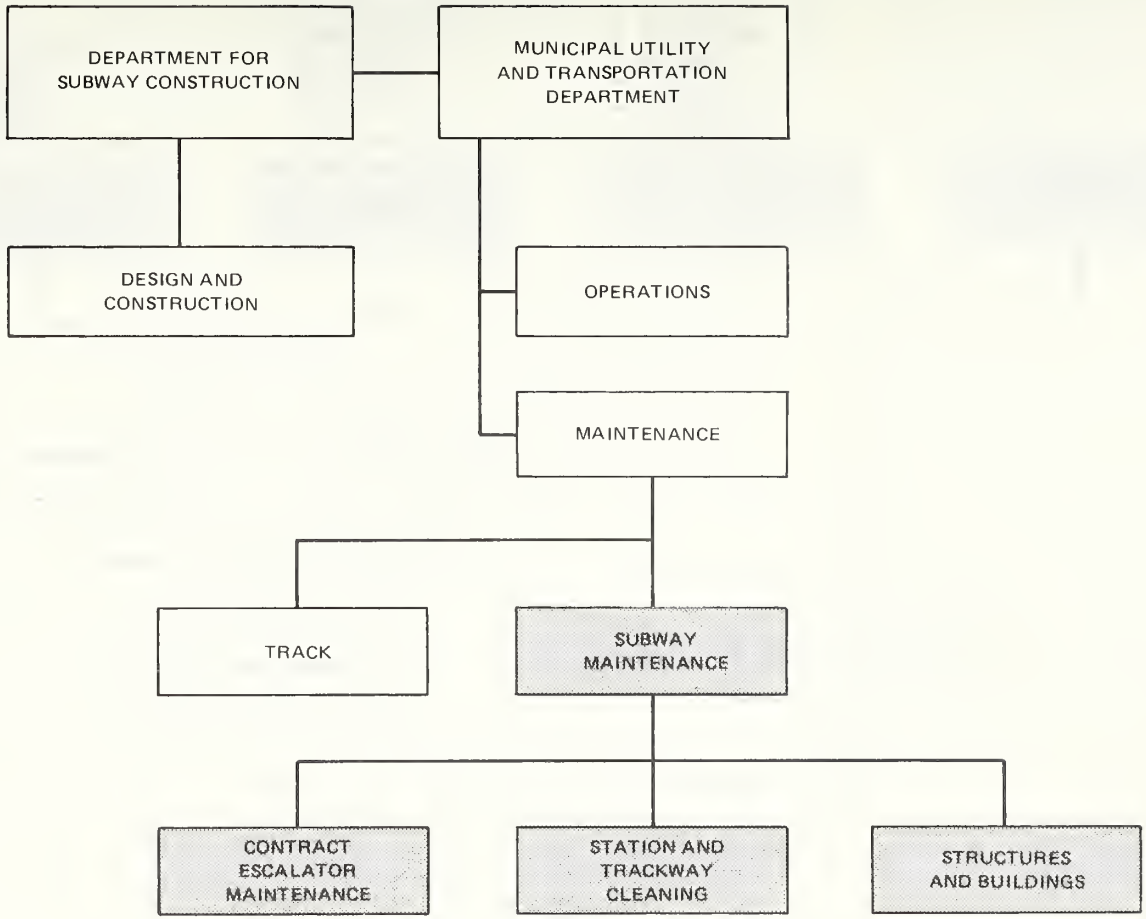


Figure 7-7. MUNICH

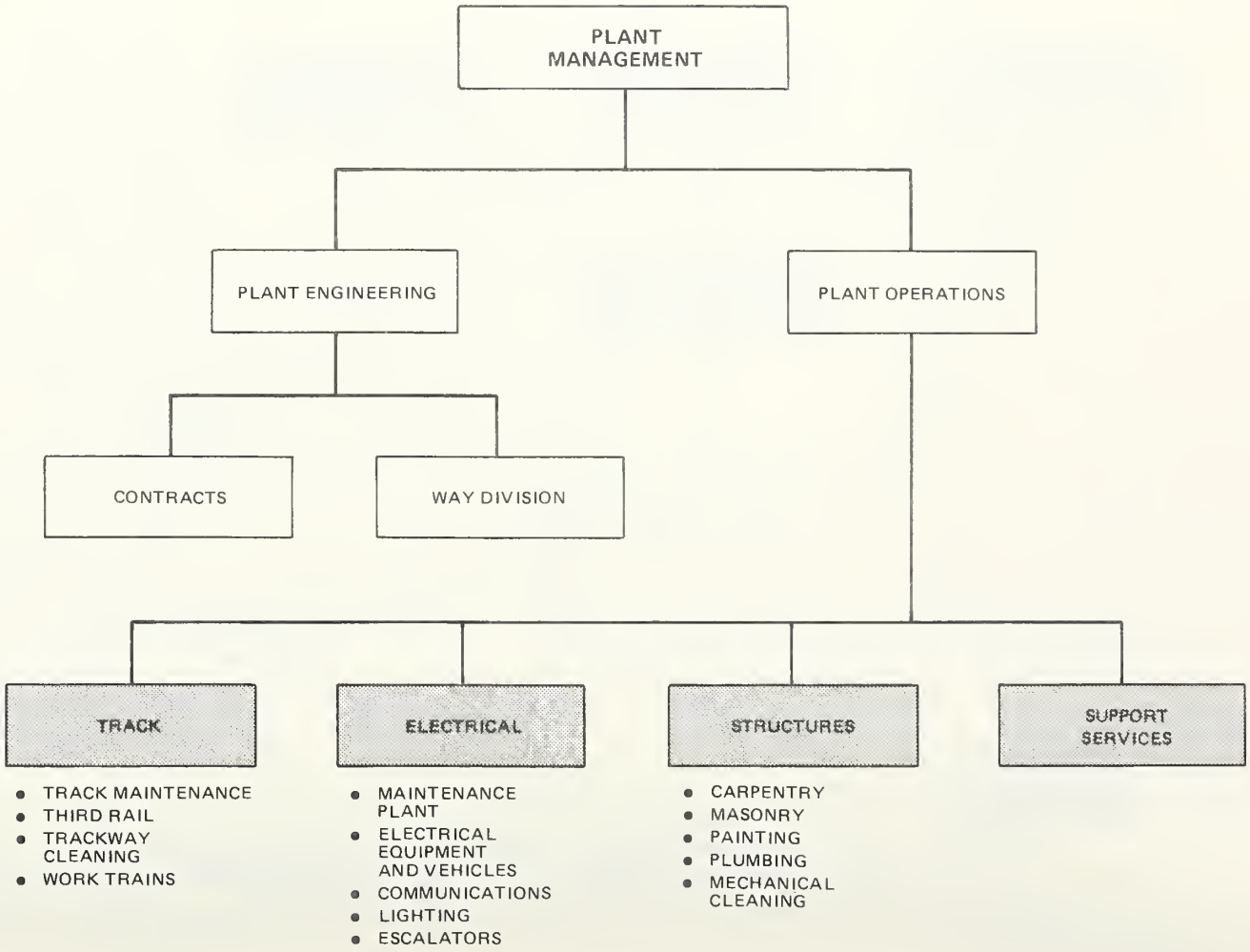


Figure 7-8. TORONTO

San Francisco

All system maintenance except for vehicles is under the direction of the Power and Way division. Figure 7-9 indicates the major division of discipline and the several task subheadings. It will be noted the section "Track and Structures" is responsible for maintenance of the trackway structure as well as the track. The escalator maintenance, presently done by contract, is being taken over by the Owner.

Chicago

The principal operations have been abstracted from the General Operations Division and are indicated in Figure 7-10. Those relating to plant maintenance and engineering have been indicated through the suboperations to the tasks. The maintenance operation embraces both "Vehicles" and "Plant," the latter being responsible for the maintenance of electrical equipment, tracks and structures, and buildings and grounds. The last three heads, among them, cover all tasks needed to maintain, including cleaning, the subway complex. Under "Engineering" are the various engineering disciplines, including architectural, for the planning, design, and construction management of new works.

Plant maintenance is performed by its own engineering staff who also provide input to the new works groups during the planning and design stages.

Boston

The Plant Maintenance division is responsible for the five group functions indicated in Figure 7-11. It will be noted that the Way and Structures Group has two subfunctions: Track and Rail and Buildings and Structures. The latter undertakes maintenance of the stations and trackway items, including the structures, but excluding lighting and auxiliary electric equipment which are the responsibility of the Signals group. Also, escalator maintenance is by outside contract.

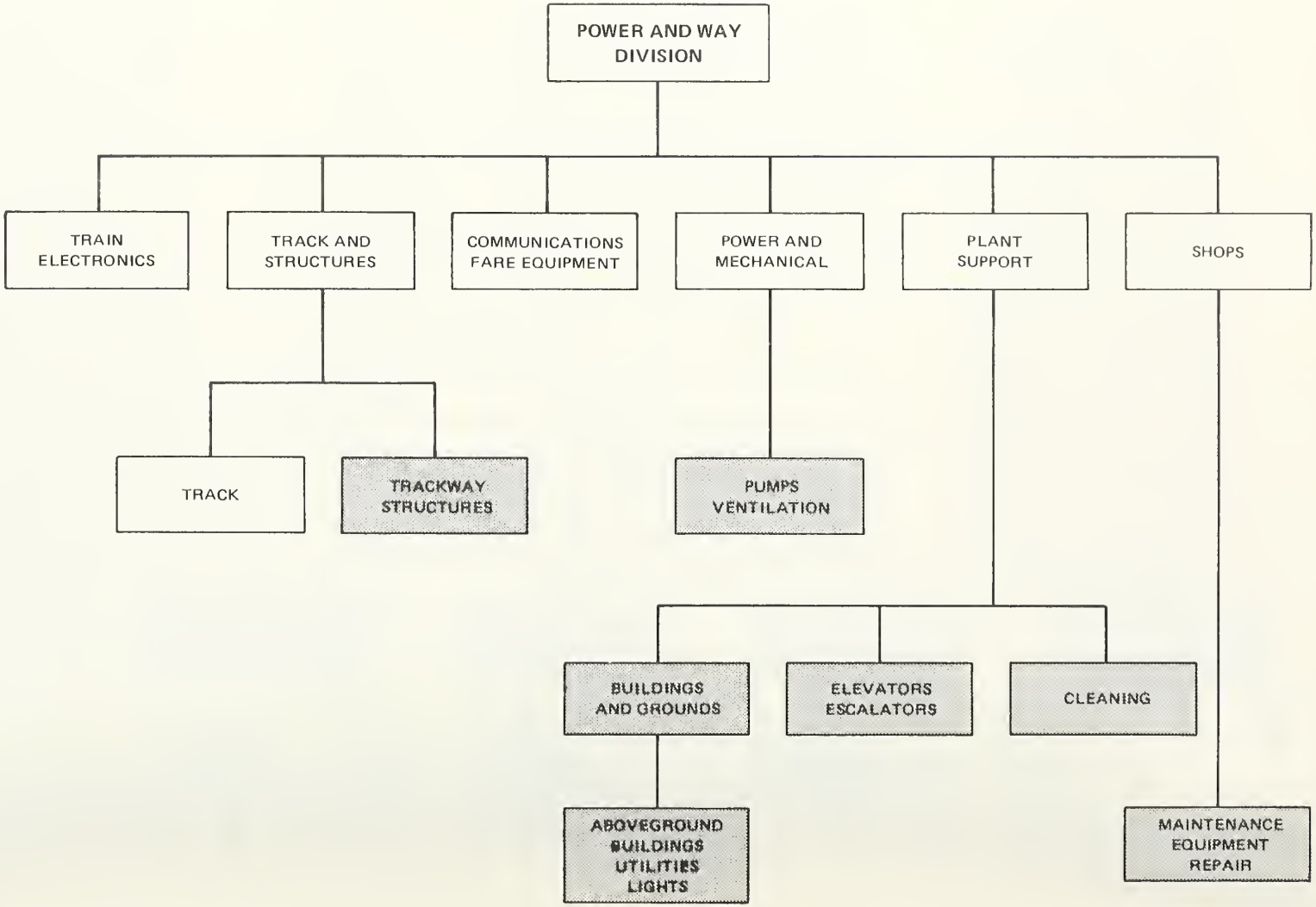


Figure 7-9. SAN FRANCISCO

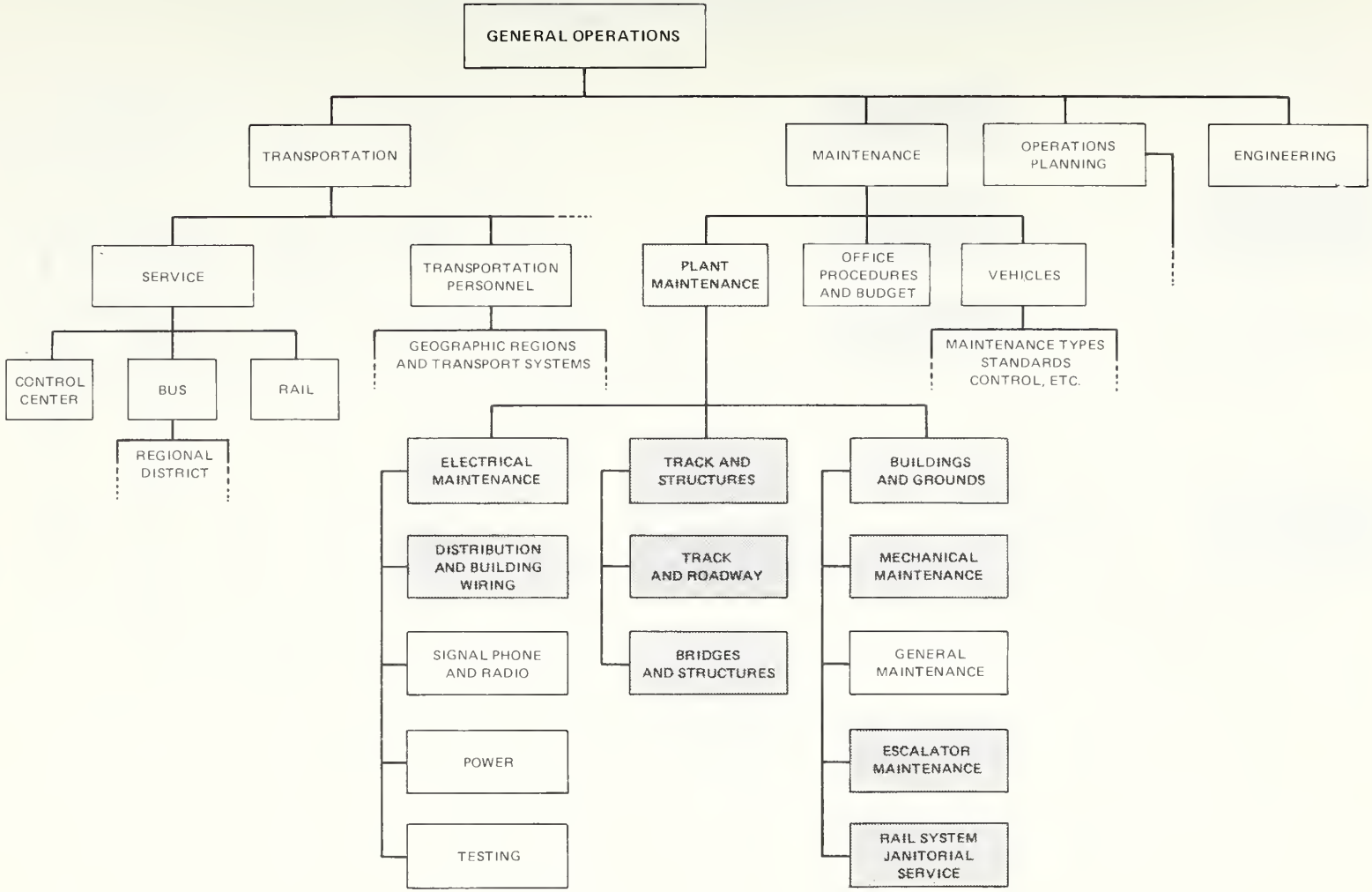


Figure 7-10. CHICAGO

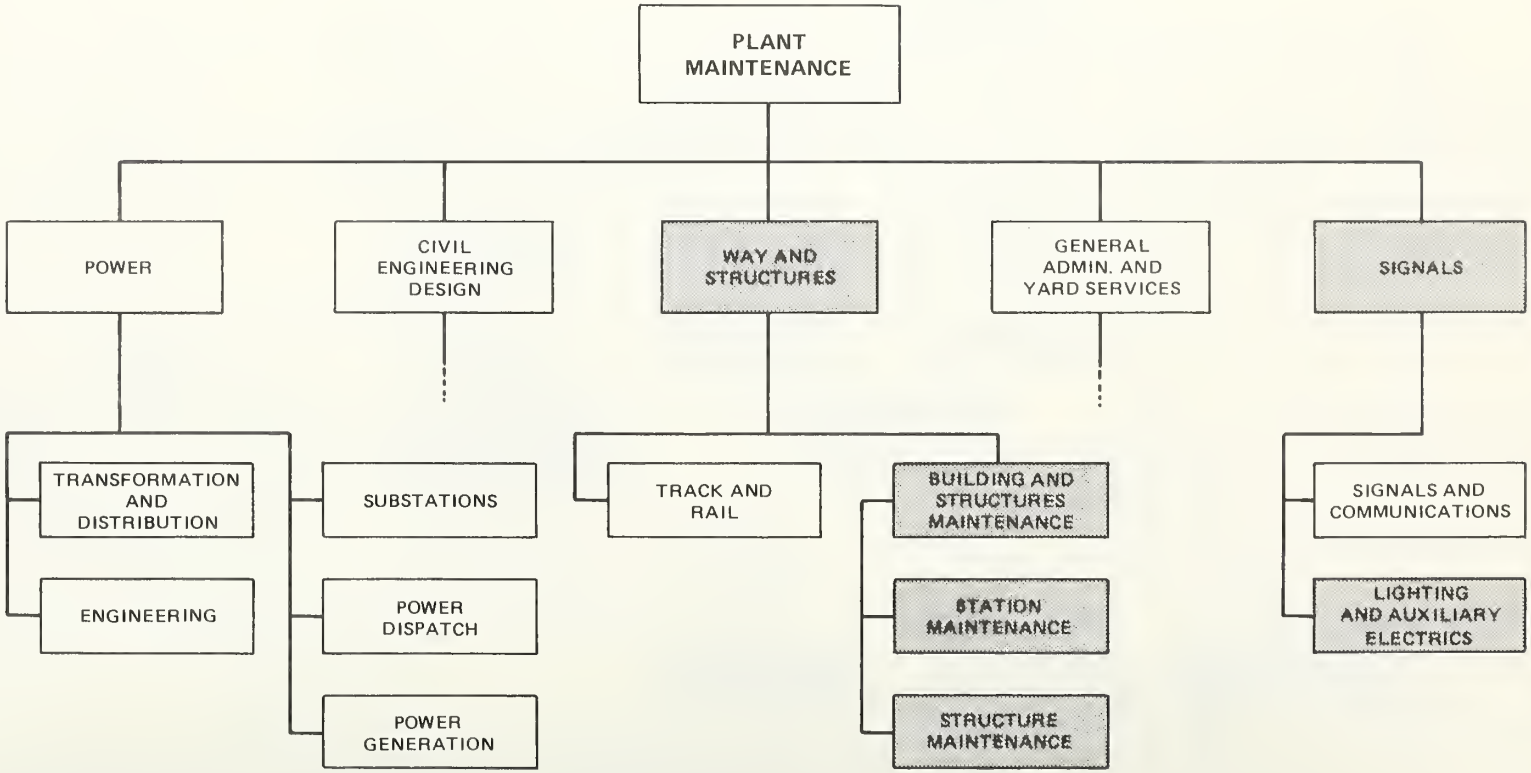


Figure 7-11. BOSTON

New York PATH

A maintenance division undertakes most of the work under the three principal subdivisions of "track," "Mechanical/Structural," and "Cleaning." The Power and Signals division, however, is responsible for the maintenance of the electrical equipment. Responsibilities for the various tasks and relationships are indicated in Figure 7-12.

New York NYCTA

The Maintenance of Way encompasses all the tasks to maintain the transit structures, track, and equipment (other that rolling stock). Figure 7-13 indicates five group functions: Signals, Line equipment, Power Distribution, Track, and Structures together with the responsibilities for individaul maintenance items that are relative to this report. Two groups, Line Equipment and Structures, share these responsibilities between them.

MAINTENANCE PROCEDURES

The displays and brief descriptions of the transit property general task organizations indicate the broad responsibilities and control of the various maintenance tasks. As could be expected, procedures for implementing the detailed tasks varied considerably among properties, and some of the more important differences and similarities invite discussion.

Two alternative approaches to maintenance work were found: by the owners' staff and by contract. The use of one or the other was generally determined by:

The type of maintenance work,
Complexity and amount of work,
Location,
Size of the transit system, and
Labor constraints.

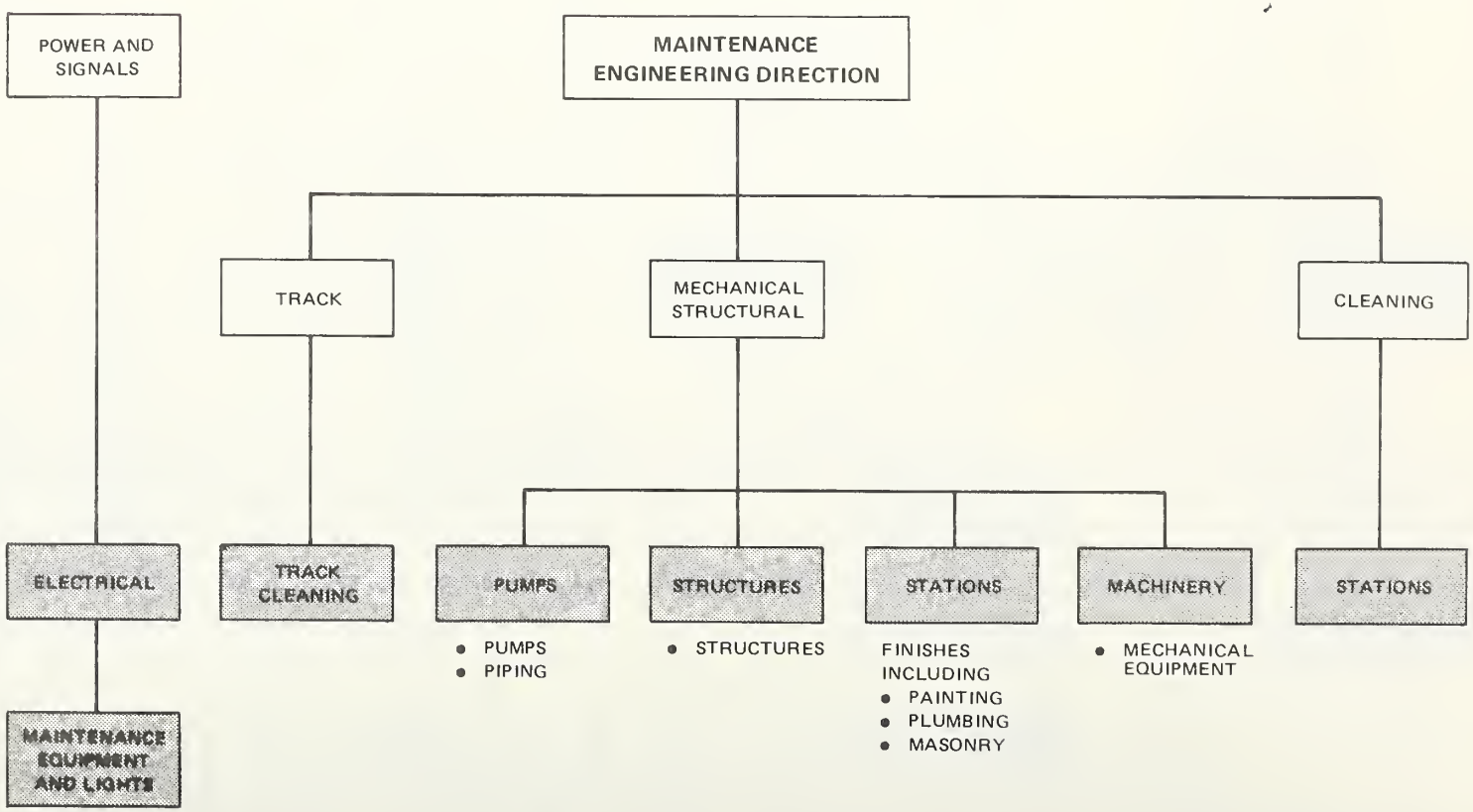


Figure 7-12. NEW YORK PATH

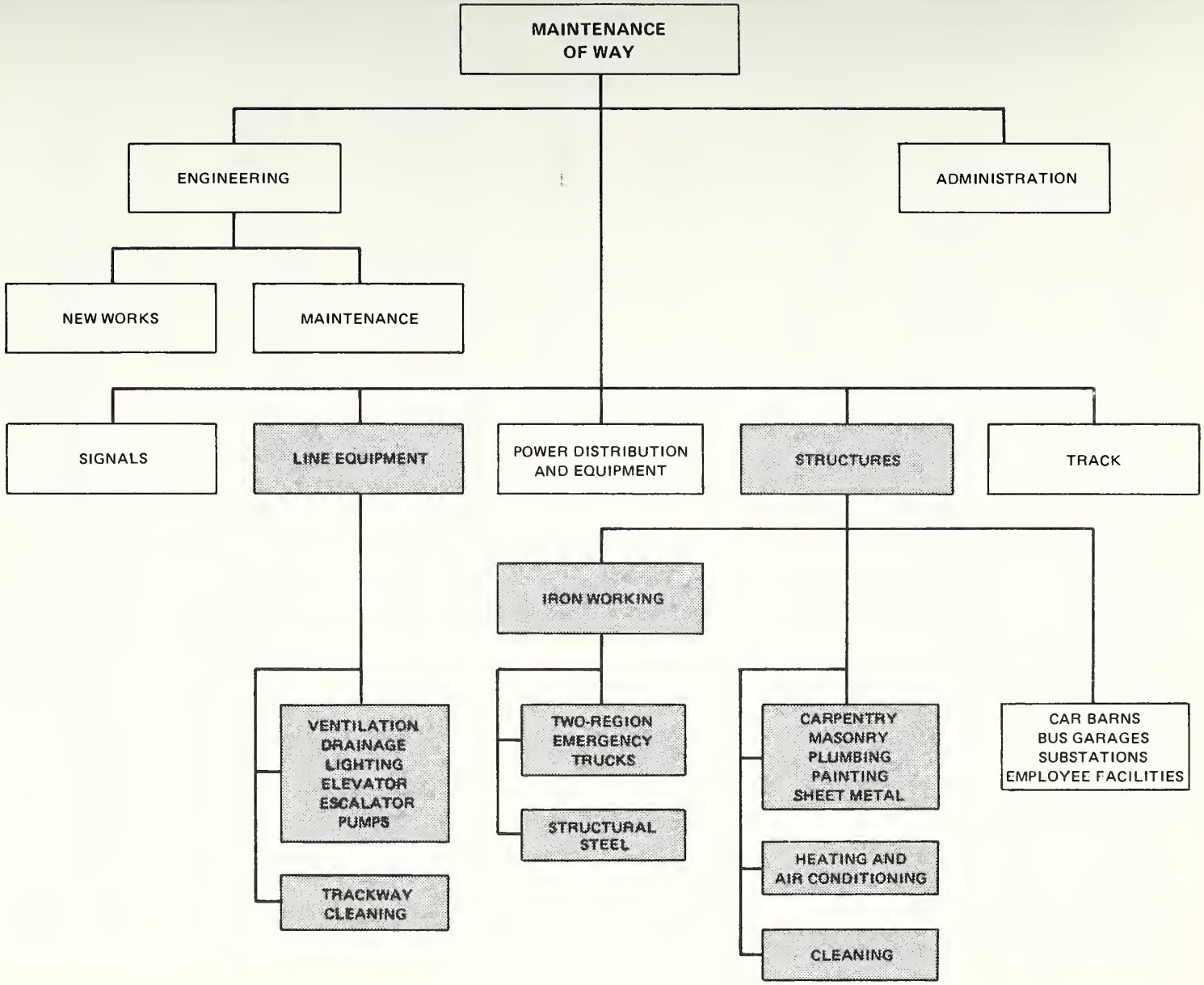


Figure 7-13. NEW YORK, NYCTA

The differing approaches to performing the maintenance work are described in the following paragraphs.

Structures

Spot repairs such as stopping leaks, repairing cracked or spalled concrete, repairing metal corrosion, etc., were undertaken by the owners. One exception was in Boston where the grouting of cracked concrete was contracted to a specialist. Paris, the only property engaged in a progressive repair of the old Metro structures, also contracted most of this work.

Escalators and Elevators

As noted in Section 4, at nearly all properties, after an initial period following the installation, the owners establish their own maintenance groups for escalators and elevators. The principal reason for this is the importance of reliable functioning of the equipment, for the efficient movement of the passenger through the station. There was reasonable consensus that the owner had better lines of communication to his own maintenance staff than to a contractor and that malfunctions, when they did occur, could be recorded and corrected most expeditiously (by the owner's staff).

At two properties, Hamburg and Boston, the maintenance work was contracted to a subsidiary company, but all work was closely integrated by the owner's maintenance staff.

Ventilation Equipment – Pump Utilities

Almost without exception routine maintenance and repair was by owners' forces.

Architectural Finishes – Including Lighting

This work is comprised of two categories – repair and replacement.

Repair, often unanticipated in a specific location but generally predictable quantitatively, usually was undertaken by the owners' forces. Such work involved a number of tradesmen (carpenters, masons, plumbers, glaziers, painters, and electricians) to repair floors, stairs, walls, ceilings, doors, plumbing, and electrical items. Repainting of ceilings and walls was also included. General replacement of items such as floors, walls, and ceilings, as in the case of Paris, was, in general, undertaken by contract.

Station Cleaning

A number of overseas properties contracted the short and long term cleaning of their stations, whereas all North Americans presently use their own staff. Policing, however, of all properties was undertaken by the owner.

New York PATH has active plans for changing their present owner-operated system to contract.

Cleaning or janitorial services for commercial properties has increasingly become an efficient and systemized commercial service. In properties such as Paris and those in Germany, it was felt that, owing to the competitive nature of these commerical services, more economic and effective results are obtained by contracting this work. Where practical, an increasing amount of equipment was being introduced to the station operation.

Trackway Cleaning

Owing to the hazardous location of the work and the nature of the operation, trackway cleaning was an owner-staffed activity. A certain amount of equipment-assisted manual cleaning was undertaken in the station platform trackway, and several properties used either vacuum or wet cleaning multiunit trains to clean the underground trackway system.

WORK FORCES AND DISPOSITIONS

The following property-by-property summary presents the data obtained on the work forces and methods used to accomplish the various types of maintenance.

In medium and large properties, it was found convenient to divide the properties into two or more geographic regions for much of the maintenance and assign unified work forces to each region; e.g., for the subway complex general maintenance and cleaning, NYCTA has five such regions, Chicago has two.

Because of the nature of the work (which in some properties includes opening and closing the stations) station policing was often organized as an individual station responsibility. Other types of maintenance, such as lighting and trackway cleaning, were performed on a system-wide basis.

London

The Works and Buildings section has organized its maintenance in six (more or less identical in composition) field task forces to operate in the six geographic areas or districts indicated in Figure 7-14. In addition, there is a seventh district comprising several workshops, depots, and (bus) garages.

The Bridges and Structures section is organized into two task forces that are responsible for maintaining the underground structures (as well as bridges) in the two geographical locations indicated in Figure 7-15. Other maintenance sections organize the work over different geographic areas, including system wide.

Figure 7-16 is a matrix depicting the group responsibilities for Inspection Cleaning and Maintenance of the various items within the subway complex (including surface installations).

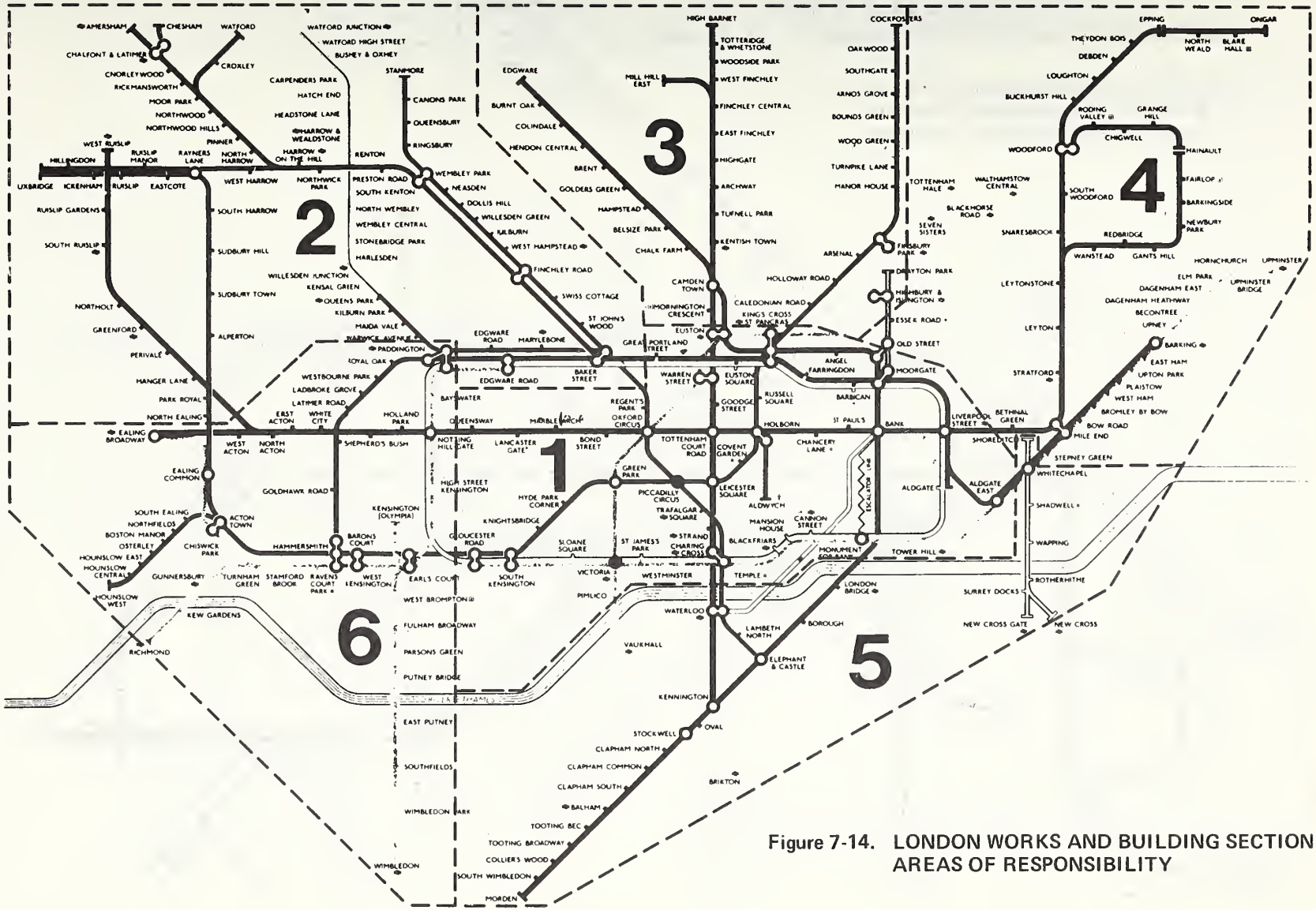


Figure 7-14. LONDON WORKS AND BUILDING SECTION AREAS OF RESPONSIBILITY

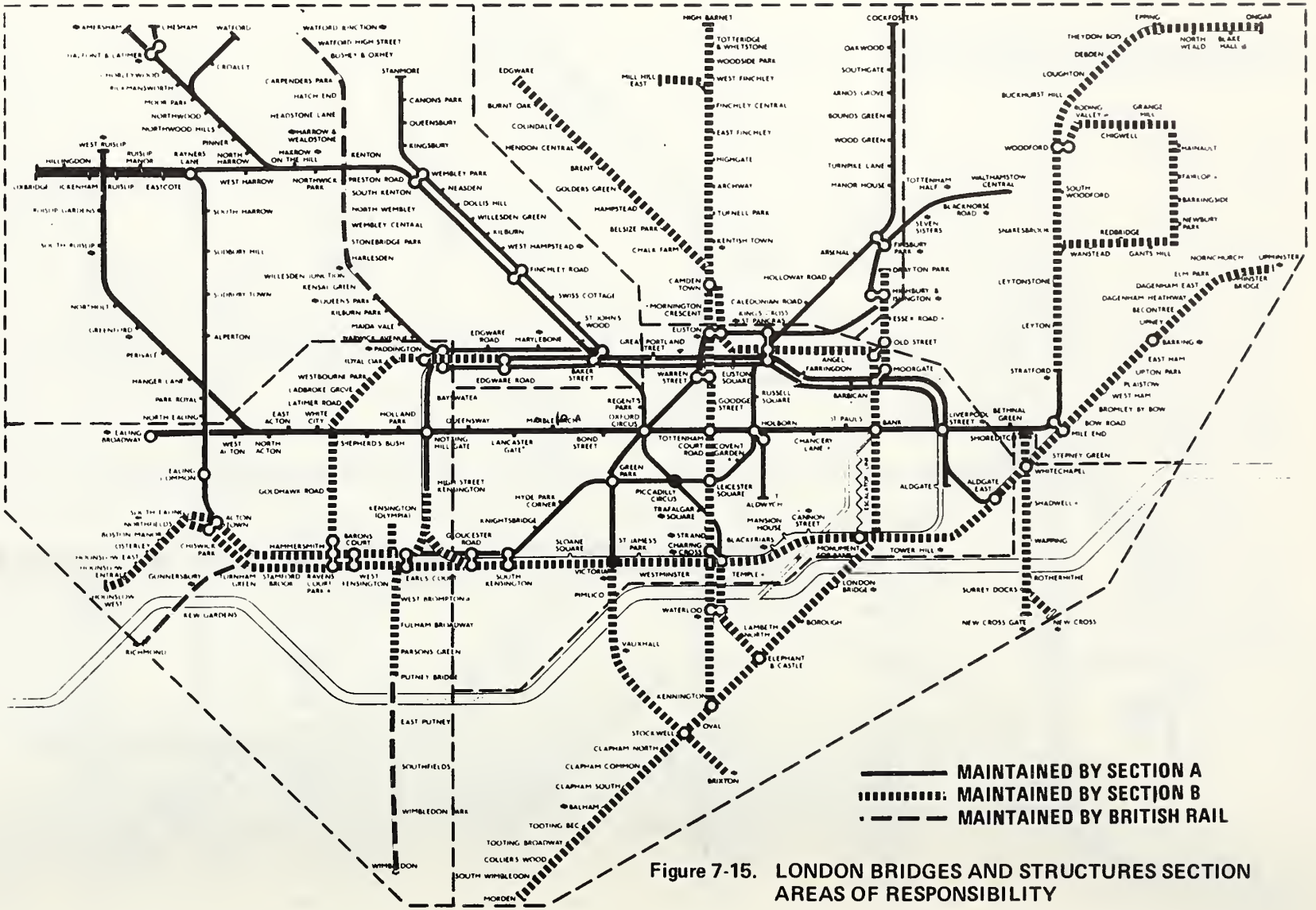


Figure 7-15. LONDON BRIDGES AND STRUCTURES SECTION AREAS OF RESPONSIBILITY

ACTIVITY	FINISHES						EQUIPMENT				ESCALATORS		LIFTS		UNDERGROUND STRUCTURE		
			WALLS														
	FLOORS	STAIRS	UP TO 6 FEET	OVER 6 FEET	CEILINGS	SKYLIGHTS	LIGHTING	PUMPS	FANS	INSULATORS FOR THIRD AND FOURTH RAIL	TOP SIDE	UNDERSIDE AND WORKS	IN CAR	WORKS	CUT-AND-COVER	DRIVEN TUNNELS	SHAFTS
INSPECTION	WB	WB	WB	WB	WB	WB	SE	LE	LE	PW	WB	LE	LE	LE	BS	BS	BS
CLEANING – Short term (janitorial)	OM	OM	OM	–	–	WB	SE	LE	LE	PW	OM	LE	OM	LE	–	–	–
CLEANING – Long term	WB	WB	WB	WB	WB	WB	SE	LE	LE	PW	WB	LE	LE	LE	WB	PW	WB
MAINTENANCE	WB	WB	WB	WB	WB	WB	SE	LE	LE	PW	WB	LE	LE	LE	BS	BS	BS

LEGEND:

OM – Railway Operating Staff
WB – Works and Building Manager
PW – Permanent Way Manager
LE – Lifts and Escalator Engineer
BS – Principal Structural Assistant (Maintenance)
SE – Signal Engineer

Figure 7-16. LONDON GROUP RESPONSIBILITIES FOR INSPECTION MAINTENANCE AND CLEANING

The Maintenance task forces are administered from three area and one system-wide headquarters. The areas and organizations, together with the personnel used, are shown in Figure 7-17. Also shown are details of the Bridges and Structures, organization responsibilities, and the administrative and engineering staff, including inspectors, required for this work.

The Manual of Inspection of Bridges, Structures and Building, defining the duties of this staff, is reproduced in Appendix 7.1.

Paris

Figure 7-18 is the Maintenance Organization Chart (translated from the French) which shows the geographical areas maintained by the various task groups. It will be noted that building maintenance, which includes Station Finishes and other items, workshops, and new works are separated into North and South areas; cleaning, administered by North Area and Structure-Tunnels and Bridges, is system wide.

As noted previously, a large proportion of the maintenance and all of the station cleaning are performed by contractors who are supervised by a proportion of the staff indicated in Figure 7-18.

It was estimated that 150 sites are occupied each night between 1 and 5 a.m., involving 2,000 work people, performing maintenance, cleaning, or renovation work. On an average, there are 100 subcontracts of 3 year duration, each generating 8,500 invoices per annum.

Preventive maintenance inspection of the structures is undertaken on a 5 to 7 year cycle, and inventories are made of work to be undertaken in the following years. Items requiring attention include replastering, painting, electrical work, and structural repair.

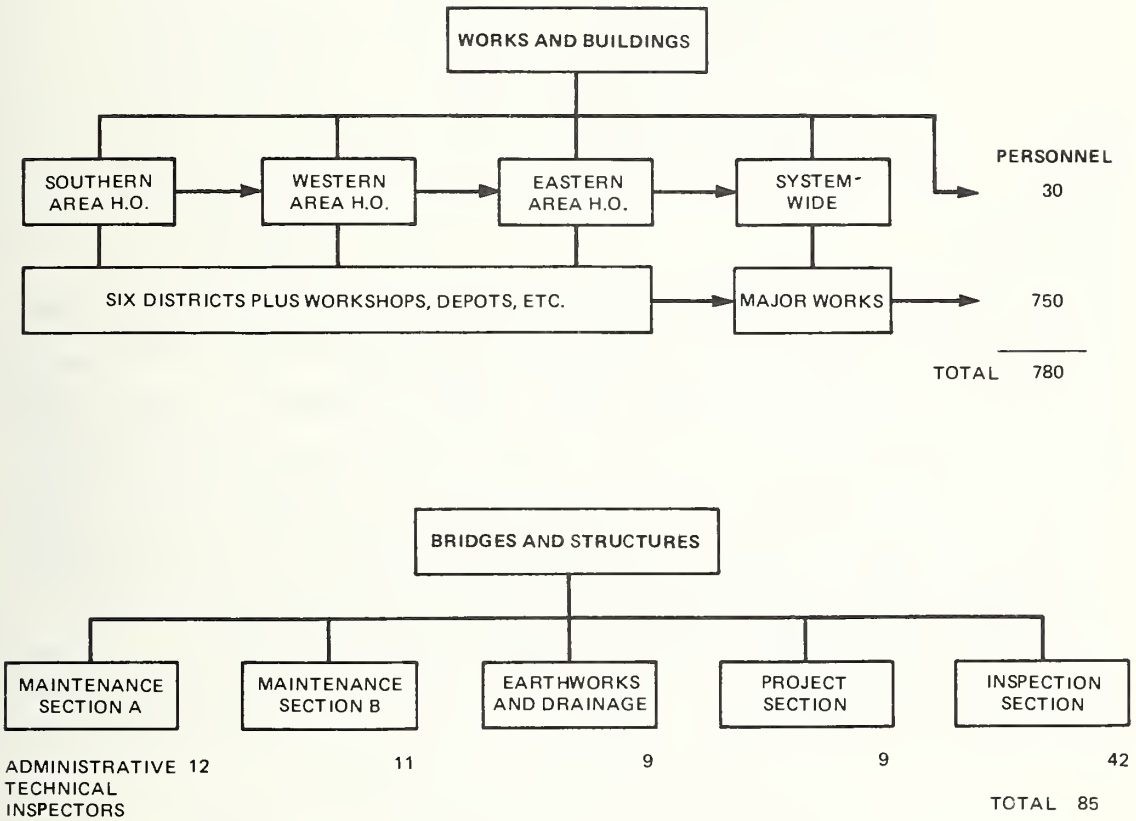


Figure 7-17. LONDON

In emergencies, the operating staff requests service by telex to the Metro workshop staff (18,000 to 20,000 requests are made per annum, or 70 per day, both in the North and South Sections). Alternative actions taken on emergency requests, depending on circumstances, may be: two people are sent to investigate the situation and will:

Correct it on the spot,
Remove the item for repair, and
Call in a subcontractor.

Toronto

Maintenance of the subway is the responsibility of the Plant Department and performed within three technical subsections: Track, Electrical, and Structures as shown in Figure 7-19. These interleave in various degrees for the maintenance of the subway. For each section, Figures 7-20, 7-21, and 7-22 indicate the manpower, the tasks, the shifts worked, and the percentage of total effort estimated to maintain (M) or clean (J) the subway system. Figure 7-23 shows the composition of the services section, and their major tasks are summarized in Figure 7-24. It will be noted that the major proportion of the maintenance and cleaning is undertaken by the structures group.

The numbers of maintenance personnel allocated to the different operations together with total manhours per year are indicated in Figure 7-25.

An analysis of the percentage figures given for the various tasks indicates:

Approximately 214 people, including administrators, are engaged in maintaining the underground structure complex,

Of these, 39, or 18 percent, maintain escalators,

13, or 6 percent, are for other maintenance activities including structures and pumps, and

162, or 76 percent, are engaged in cleaning, of which 145 are required for the stations.

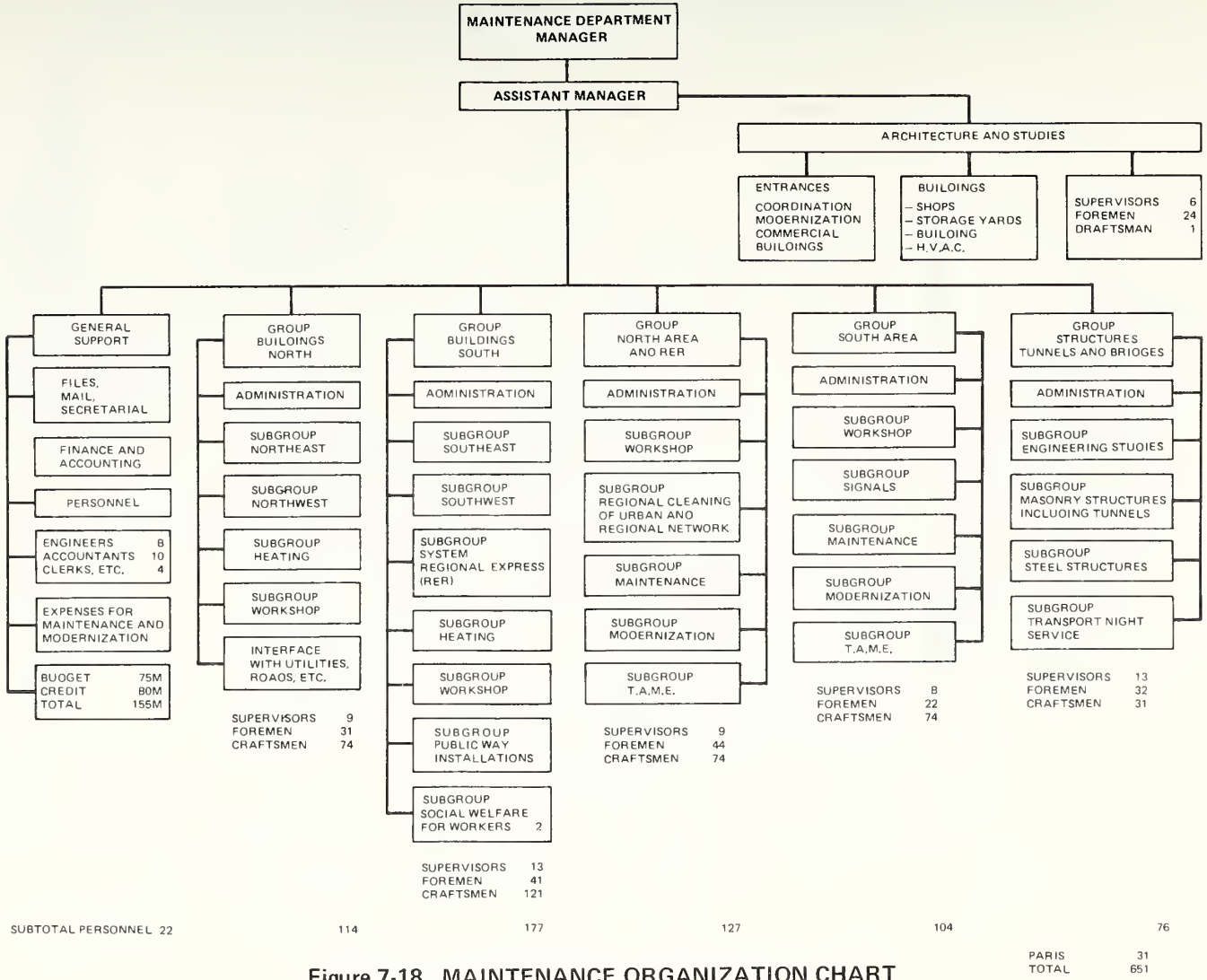


Figure 7-18. MAINTENANCE ORGANIZATION CHART

SUBWAY MAINTENANCE — TECHNICAL SUBSECTIONS

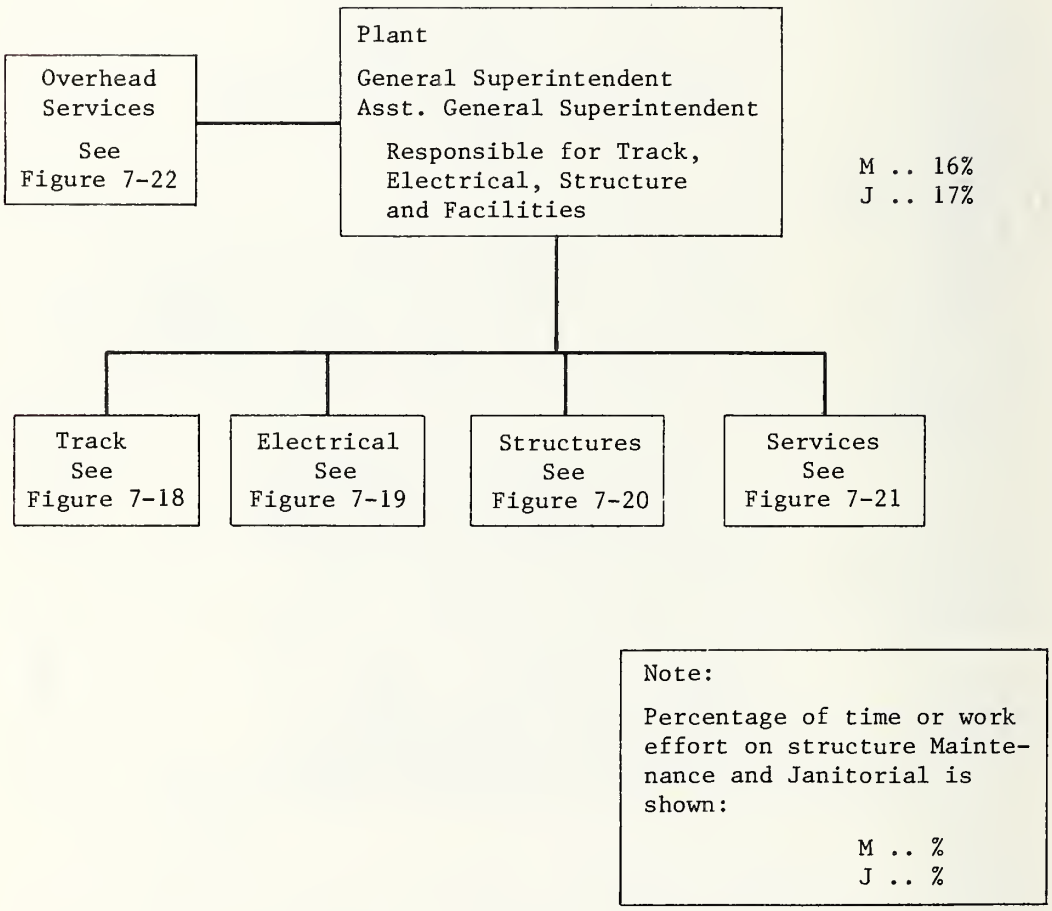


Figure 7-19. TECHNICAL SUBSECTIONS FOR MAINTENANCE

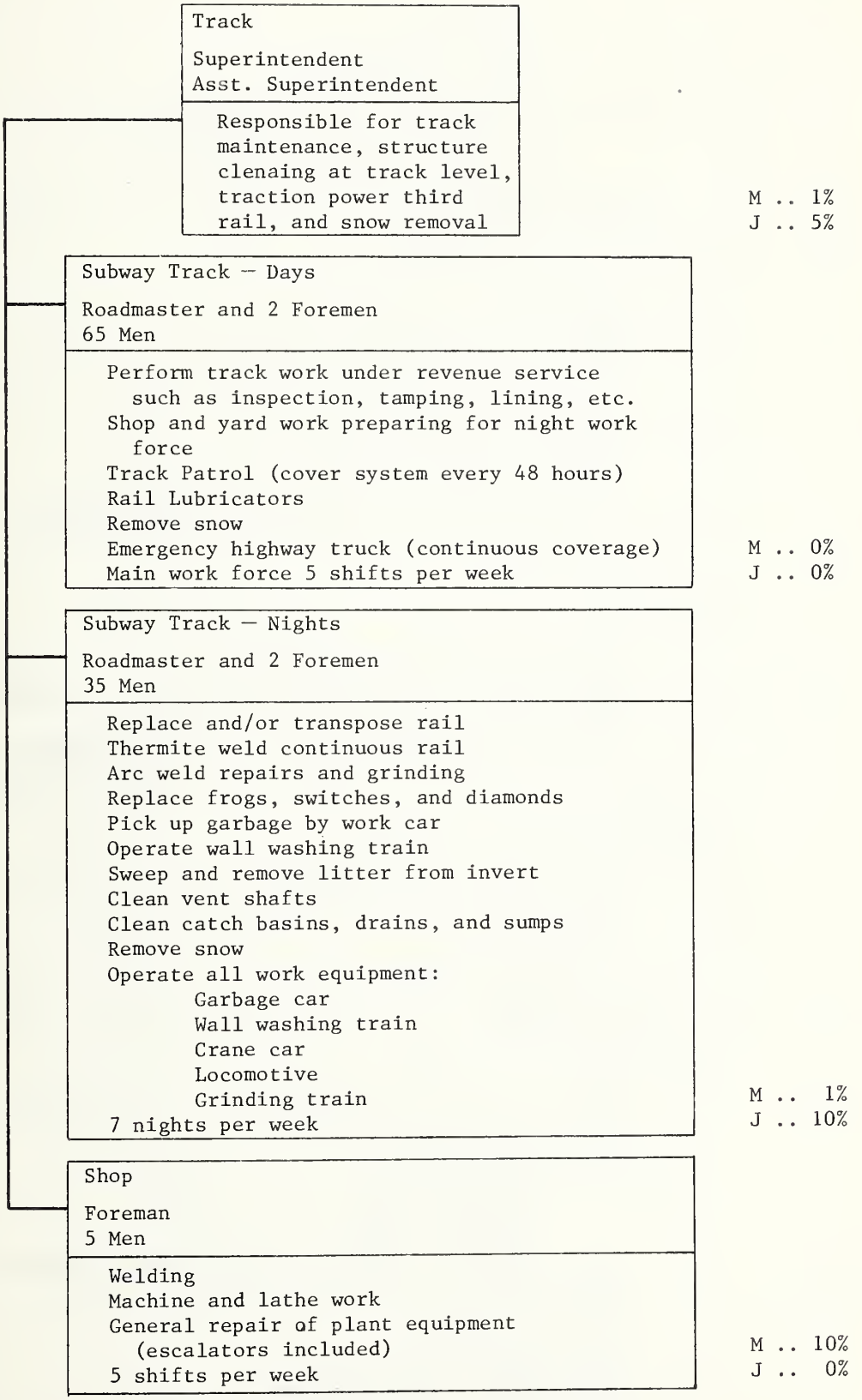


Figure 7-20. TRADE MANPOWER – TRACK

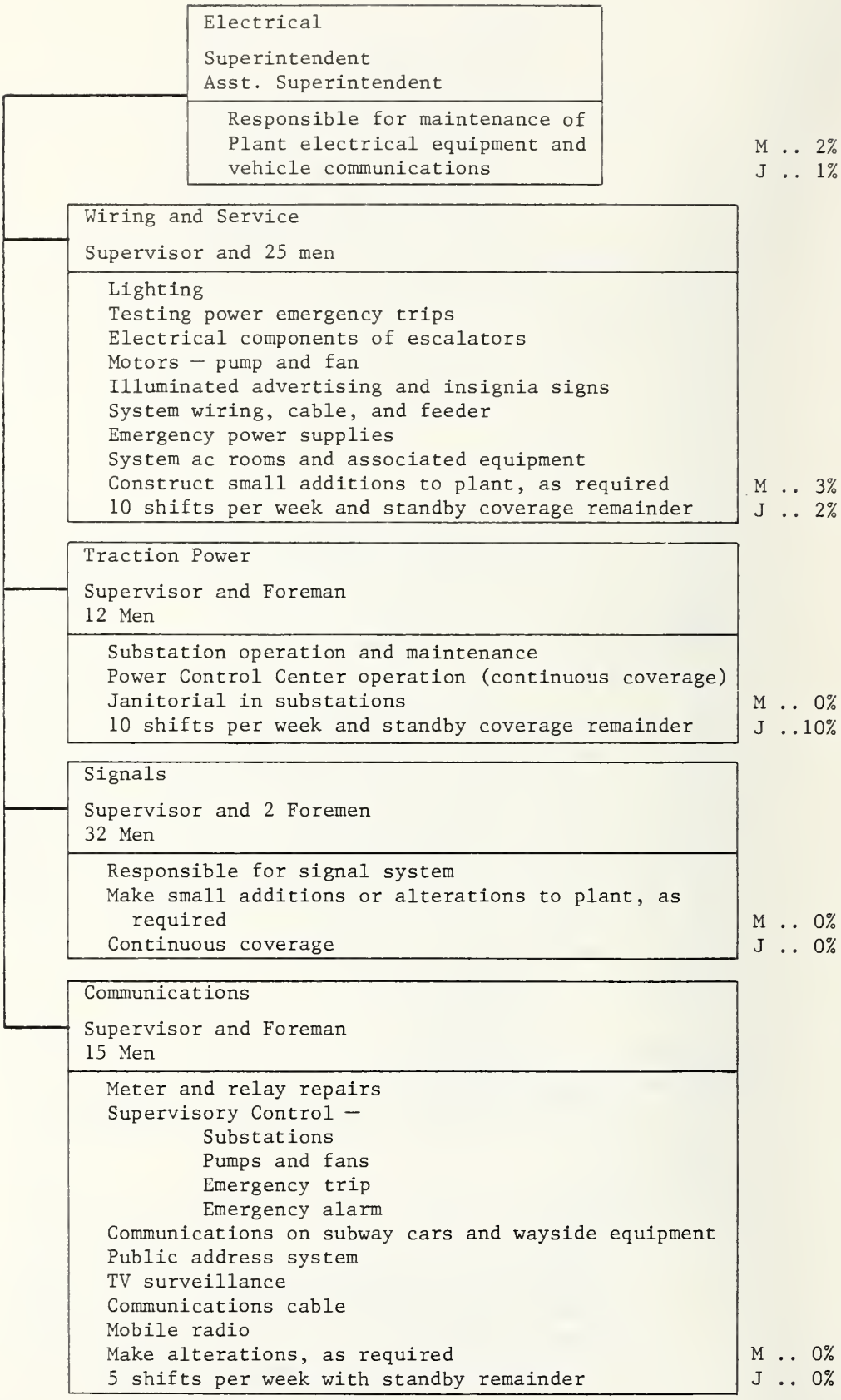


Figure 7-21. TRADE MANPOWER — ELECTRICAL

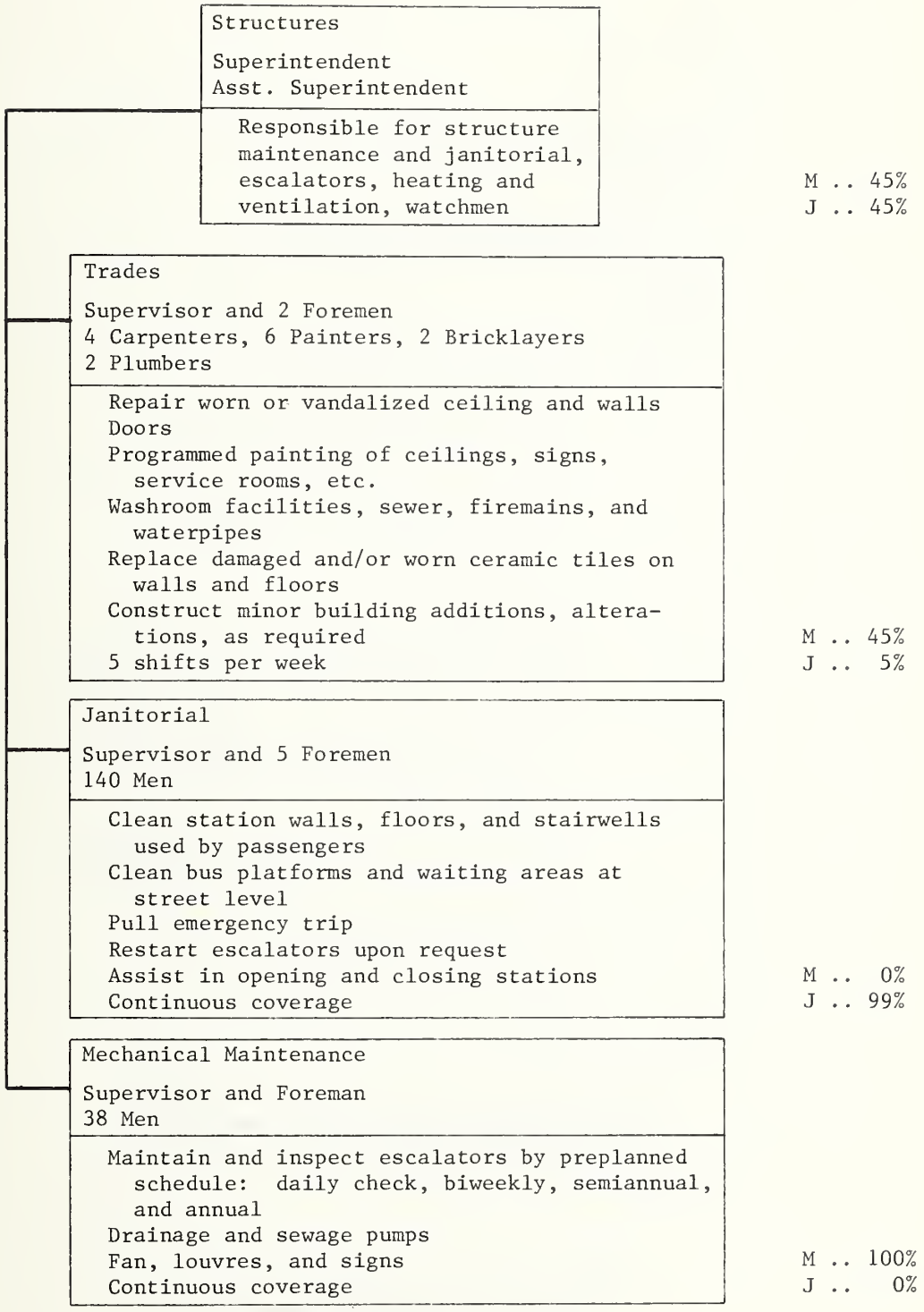

Structures
Superintendent
Asst. Superintendent
Responsible for structure maintenance and janitorial, escalators, heating and ventilation, watchmen
M .. 45%
J .. 45%
Trades
Supervisor and 2 Foremen
4 Carpenters, 6 Painters, 2 Bricklayers
2 Plumbers
Repair worn or vandalized ceiling and walls
Doors
Programmed painting of ceilings, signs, service rooms, etc.
Washroom facilities, sewer, firemains, and waterpipes
Replace damaged and/or worn ceramic tiles on walls and floors
Construct minor building additions, alterations, as required
5 shifts per week
M .. 45%
J .. 5%
Janitorial
Supervisor and 5 Foremen
140 Men
Clean station walls, floors, and stairwells used by passengers
Clean bus platforms and waiting areas at street level
Pull emergency trip
Restart escalators upon request
Assist in opening and closing stations
Continuous coverage
M .. 0%
J .. 99%
Mechanical Maintenance
Supervisor and Foreman
38 Men
Maintain and inspect escalators by preplanned schedule: daily check, biweekly, semiannual, and annual
Drainage and sewage pumps
Fan, louvres, and signs
Continuous coverage
M .. 100%
J .. 0%

Figure 7-22. TRADE MANPOWER – STRUCTURES

Services		
17 Persons reporting mostly to the Asst. General Superintendent		
No. of Persons	Functions	
4	Plant Maintenance Control (PMC) Continuous coverage Receive and log emergency calls and then advise appropriate person Nerve center for maintenance functions	
2	Cost estimating, procurement of special material, and special project management	
2	Procurement of materials from stock and special orders Work closely with Materials Department Check inventory with auditors	
1	Office administration: prepare power cut program and many duties at senior level	
1	Work methods and computer scheduling; work closely with computer services	
4	Timekeeping and employee records	M .. 20%
3	General clerks and typing	J .. 10%

Note:

The services are for subway and surface (streetcar, bus, and trolley coach) operations. Approximately 9 persons time chargeable to subway.

Figure 7-23. SERVICES MANPOWER

Overhead Services

Plant Administrative (controlled by Plant Department)

Cost analysis
Budget control and information for supervisors
Liaison between maintenance function and computer center
Track engineering, design improvements
Ultrasonic rail, welds, and bolt hole testing
Track rideability testing
Electrical engineering, circuit drawing changes, etc.
Studies on electrolysis, etc.
Long range electrical planning
Preparation of drawings for building alterations and small new structures
Design heating and ventilating changes
General office administration, report writing, etc.

Services from Outside Plant Department

Materials Department: stores, stock, and purchasing
Treasury Department: cost accounting, budget, cost control
Computer Center: work scheduling, cost reports
Safety Department: accident prevention, both personal and property
Equipment Department: plant maintains their buildings; they maintain plant work equipment
Transportation Department: close liaison on operating matters
Personnel Department: staff recruitment, training, Union administration, job evaluation, personnel benefits, and records
Consultants: tunnel leaks, electrolysis, bridges
Contract Work: new station finishes, new ceilings, grouting, building alterations, etc.

Note:

All the services on this sheet are essential for the operation of the Structure Division. The costs of these services are included in the general overhead.

Figure 7-24. SERVICES TASKS

AREA	ORGANIZATION PERSONNEL				MAINTENANCE			JANITORIAL			REMAINDER		
	Manage-ment	Super-visor Foremen	Labor	Total	Proportion Due to Maintenance (%)	Man-Hours per Year (h)	Proportion per Item (%)	Proportion Due to Janitorial (%)	Man-Hours per Year (h)	Proportion per Item (%)	Proportion Due to Remainder (%)	Man-Hours per Year (h)	Proportion per Item (%)
TRACK													
Management	2			2	1	40	0	5	200	0	94	3,760	1
Subway track — Days		3	65	68	0	0	0	0	0	0	100	136,000	32
— Nights		3	35	38	1	760	1	10	7,600	2	89	67,640	16
Shop		1	5	6	10	1,200	1	0	0	0	90	10,800	2
ELECTRICAL													
Management	2			2	2	80	0	1	40	0	97	3,880	1
Wiring and service		1	25	26	3	1,560	2	2	1,040	0	95	49,400	11
Traction power		2	12	14	0	0	0	10	2,800	1	90	25,200	6
Signals		3	32	34	0	0	0	0	0	0	100	68,000	16
Communications		2	15	17	0	0	0	0	0	0	100	34,000	8
STRUCTURES													
Management	2			2	45	1,800	2	45	1,800	1	10	400	1
Trades		3	14	17	45	15,300	14	45	15,300	5	10	3,400	
Janitorial		6	140	146	0	0	0	99	289,080	90	1	2,920	1
Mechanical maintenance		2	38	40	100	80,000	74	0	0	0	0	0	0
SERVICES			17	17	20	6,800	6	10	3,400	1	70	23,800	5
TOTAL				429		107,540	100%		321,260	100%		429,200	100%

Figure 7-25. TORONTO TRANSIT COMMISSION BREAKDOWN OF OPERATION ITEMS

Chicago

The various maintenances are subdivided into areas or geographic subdivisions according to the character of the work involved. Figure 7-26 indicates the areas and their interrelationship, and it will be noted that these are:

Area (or system) wide,
South region and north region,
Districts A B (south region), and
Districts C D (north region).

The underground complex is maintained by Plant Maintenance, Building and Grounds section, as indicated in Figure 7-10. The approximate number of personnel assigned to the four task subsections of General Maintenance, Mechanical, Electrical, and Cleaning and their geographic responsibilities, is displayed in Figure 7-27.

Out of the total Plant Maintenance personnel of 1,070, 594 are assigned to the maintenance of the fixed plant (not including track power vehicles, etc.). The route length of the subway section is about 9 miles, out of 90 for the total system, and Chicago estimates the following distribution of costs.

PLANT MAINTENANCE

Area	% of Plant Mtc. Total Rapid Transit System Maintenance Costs	
	Total Rapid Transit System	Subway Only
Station cleaning	23%	7%
Escalators	4	2
Station and structure repairs	15	3
Other (w/o traction power)	58	4
Total	100%	16%

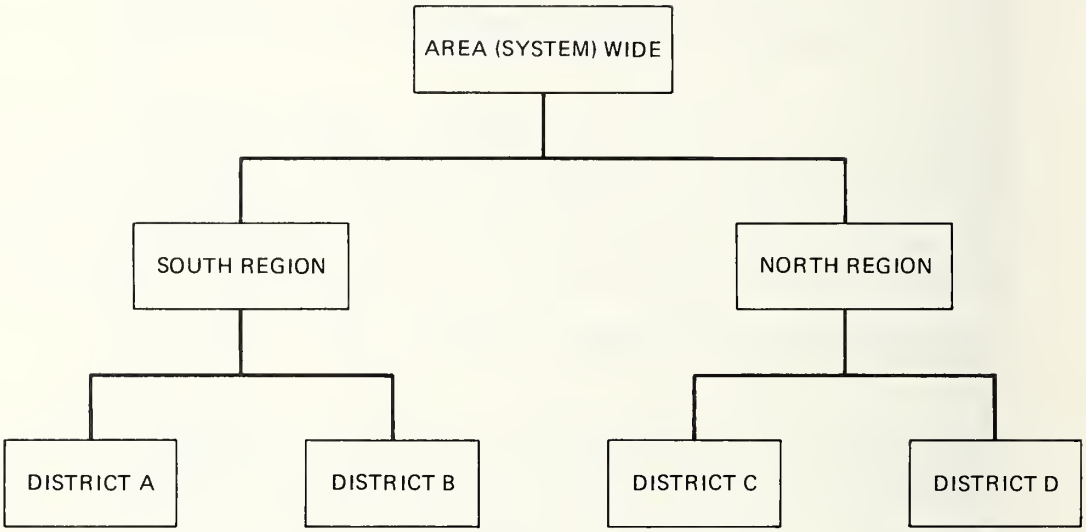


Figure 7-26. CHICAGO GEOGRAPHIC DIVISIONS OF MAINTENANCE

GEOGRAPHIC LOCALITY		GENERAL MAINTENANCE (STRUCTURES & ARCHITECTURE)		MECHANICAL		ELECTRICAL		CLEANING	
1	AREAWIDE	1	GROUP SUPERVISOR		SHEET METAL		LIGHTS		JANITORIAL
		4	BUILDING INSPECTORS	1	GROUP SUPERVISOR	1	FOREMAN	1	GROUP SUPERVISOR
		5		2	FOREMEN	21	TRADES		
				25	TRADES	22			
				28					
					MECHANICAL SYSTEMS				
				1	GROUP SUPERVISOR				
				3	FOREMEN				
				44	TRADESMEN				
				48					
					ESCALATORS				
				1	GROUP SUPERVISOR				
				2	INSPECTORS				
				20	MECHANICS				
				23					
2	REGIONS NORTH AND SOUTH		MASONRY		MACHINIST UNIT				
		1	FOREMAN	2	FOREMEN			3	UNIT SUPERVISORS
		12	TRADES	34	TRADES			2	DISPATCHERS
3	DISTRICTS	13		36				5	
	A		CARPENTRY PAINTING						
	B								
	C	17	FOREMEN					19	SUBUNIT SUPERVISORS
	D	133	TRADES					219	JANITORS
		155						238	
TOTAL PERSONNEL		173		155		22		244	GRAND TOTAL

Figure 7-27. CHICAGO ORGANIZATION CHART MAINTENANCE TASKS

The plant maintenance costs (total rapid transit system) represents 21 percent of the total rapid transit operating cost which includes rail vehicle maintenance, traction power, and all other transportation costs.

New York NYCTA

The five geographic areas for structure maintenance are shown on Figure 7-28, and Figure 7-29 indicates the Maintenance of Way Department's inspection organization and subdivision work groups. The subway structures maintenance work force, indicated by general trades for one subdivision (3), is:

1 Supervisor,
2 Assistant supervisors,
32 Carpenters, 4 foremen,
48 Masons (including concrete workers), 6 foremen,
30 Sheetmetal workers, 4 foremen,
29 Plumbers, 4 foremen, and
21 Painters, 3 foremen.

In addition, leak gangs composed of masons and plumbers are provided on a system-wide basis. Where required, work trains with the necessary equipment, including compressors, welders, etc., are used. The maintenance undertaken and planned by organizations in each of the five areas is reported monthly.

A general inspection for structural defects is made monthly with more detailed inspections every six months.

The 102 escalators and 28 elevators are maintained by 62 mechanics plus additional workshop staff. Cleaning of a typical station requires:

Policing: 2 men for two 8-hour shifts, 7 days a week, and

Heavy Duty Cleaning: 4 men for 8 hours with 1 supervisor for 4 stations; mechanical equipment includes 750 psi washers and mechanical scrubbers for use on terrazzo floors.

The structures maintenance organization includes a subgroup of Iron Workers with two sections that perform all the structural steel maintenance work for the north and south geographic areas indicated in Figure 7-30. The Iron Workers are also responsible for the operation of two fully equipped emergency trucks located one in each area.

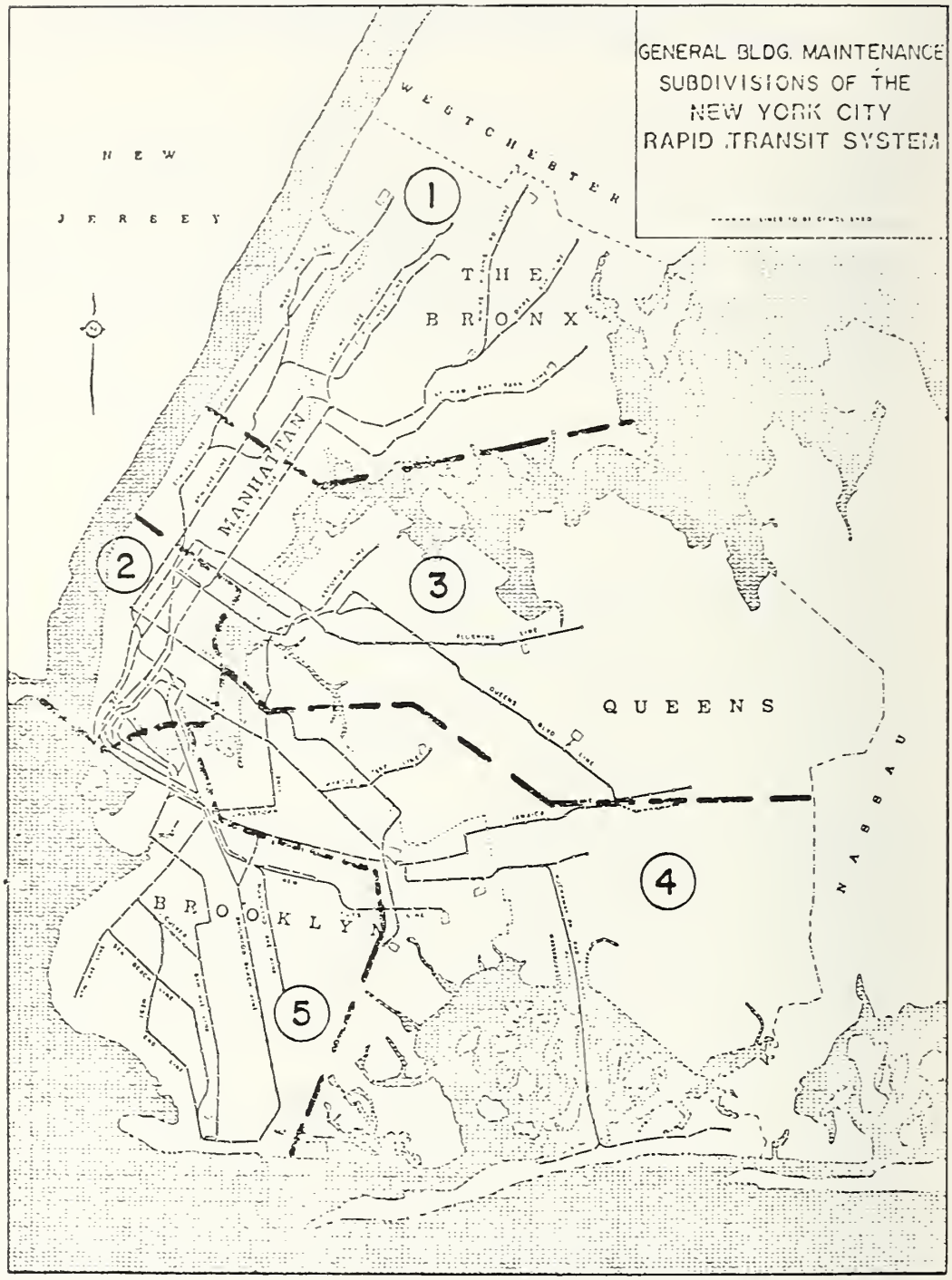


Figure 7-28. STRUCTURE MAINTENANCE GEOGRAPHICAL DIVISIONS

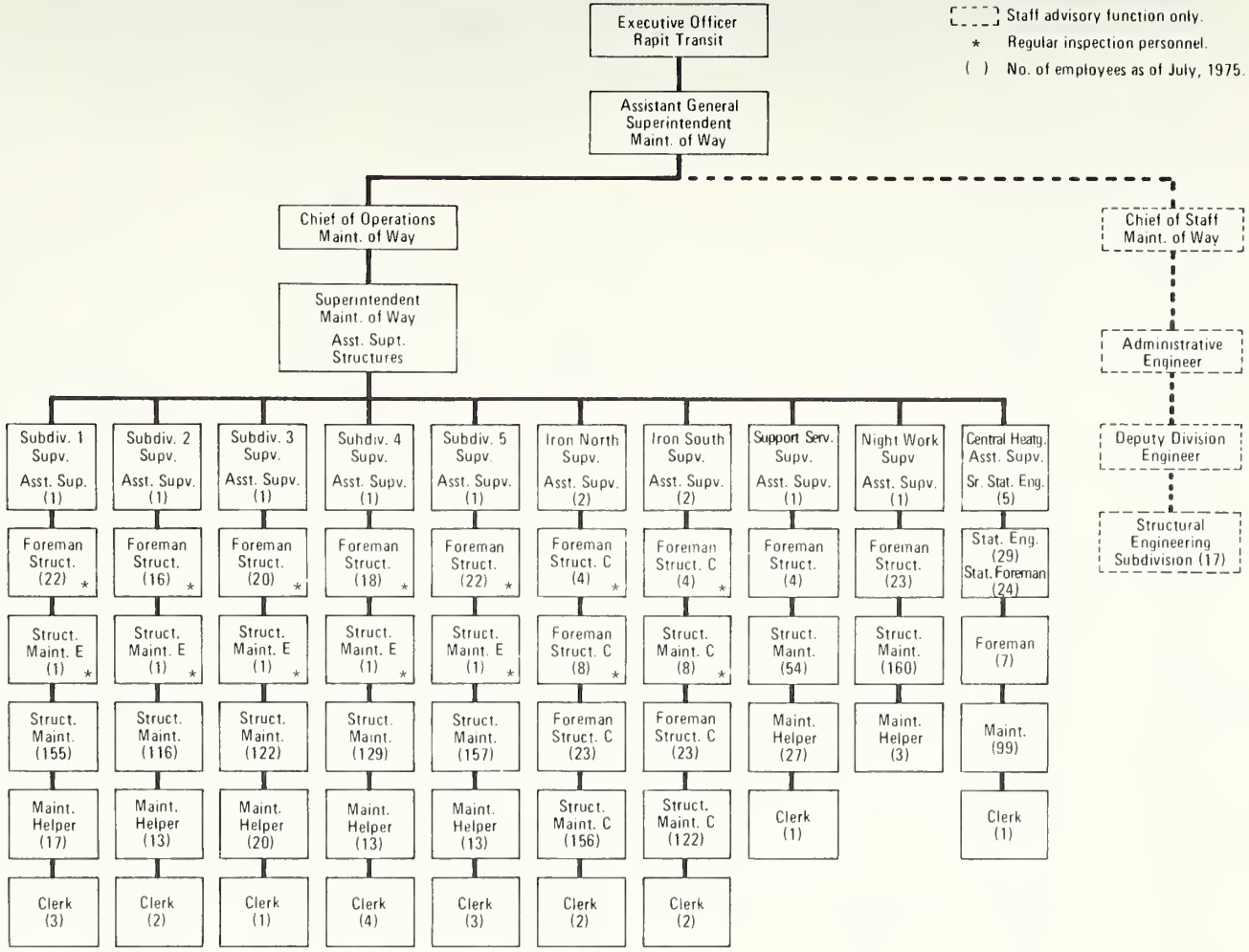

Executive Officer Rapit Transit
Assistant General Superintendent Maint. of Way
Chief of Operations Maint. of Way
Superintendent Maint. of Way
Asst. Supt. Structures
Chief of Staff Maint. of Way
Administrative Engineer
Deputy Division Engineer
Structural Engineering Subdivision (17)
Staff advisory function only.
* Regular inspection personnel.
( ) No. of employees as of July, 1975.
Subdiv. 1 Supv. Asst. Sup. (1)
Subdiv. 2 Supv. Asst. Supv. (1)
Subdiv. 3 Supv. Asst. Supv. (1)
Suhdiv. 4 Supv. Asst. Supv. (1)
Subdiv. 5 Supv. Asst. Supv. (1)
Iron North Supv. Asst. Supv. (2)
Iron South Supv. Asst. Supv. (2)
Support Serv. Supv. Asst. Supv. (1)
Night Work Supv Asst. Supv. (1)
Central Heatg. Asst. Supv. Sr. Stat. Eng. (5)
Foreman Struct. (22) *
Foreman Struct. (16) *
Foreman Struct. (20) *
Foreman Struct. (18) *
Foreman Struct. (22) *
Foreman Struct. C (4) *
Foreman Struct. C (4) *
Foreman Struct. (4)
Foreman Struct. (23)
Stat. Eng. (29) Stat. Foreman (24)
Struct. Maint. E (1) *
Struct. Maint. E (1) *
Struct. Maint. E (1) *
Struct. Maint. E (1) *
Struct. Maint. E (1) *
Foreman Struct. C (8) *
Struct. Maint. C (8) *
Struct. Maint. (54)
Struct. Maint. (160)
Foreman (7)
Struct. Maint. (155)
Struct. Maint. (116)
Struct. Maint. (122)
Struct. Maint. (129)
Struct. Maint. (157)
Foreman Struct. C (23)
Foreman Struct. C (23)
Maint. Helper (27)
Maint. Helper (3)
Maint. (99)
Maint. Helper (17)
Maint. Helper (13)
Maint. Helper (20)
Maint. Helper (13)
Maint. Helper (13)
Struct. Maint. C (156)
Struct. Maint. C (122)
Clerk (1)
Clerk (1)
Clerk (3)
Clerk (2)
Clerk (1)
Clerk (4)
Clerk (3)
Clerk (2)
Clerk (2)

Figure 7-29. DETAIL OF MAINTENANCE OF WAY DEPARTMENT INSPECTION ORGANIZATION

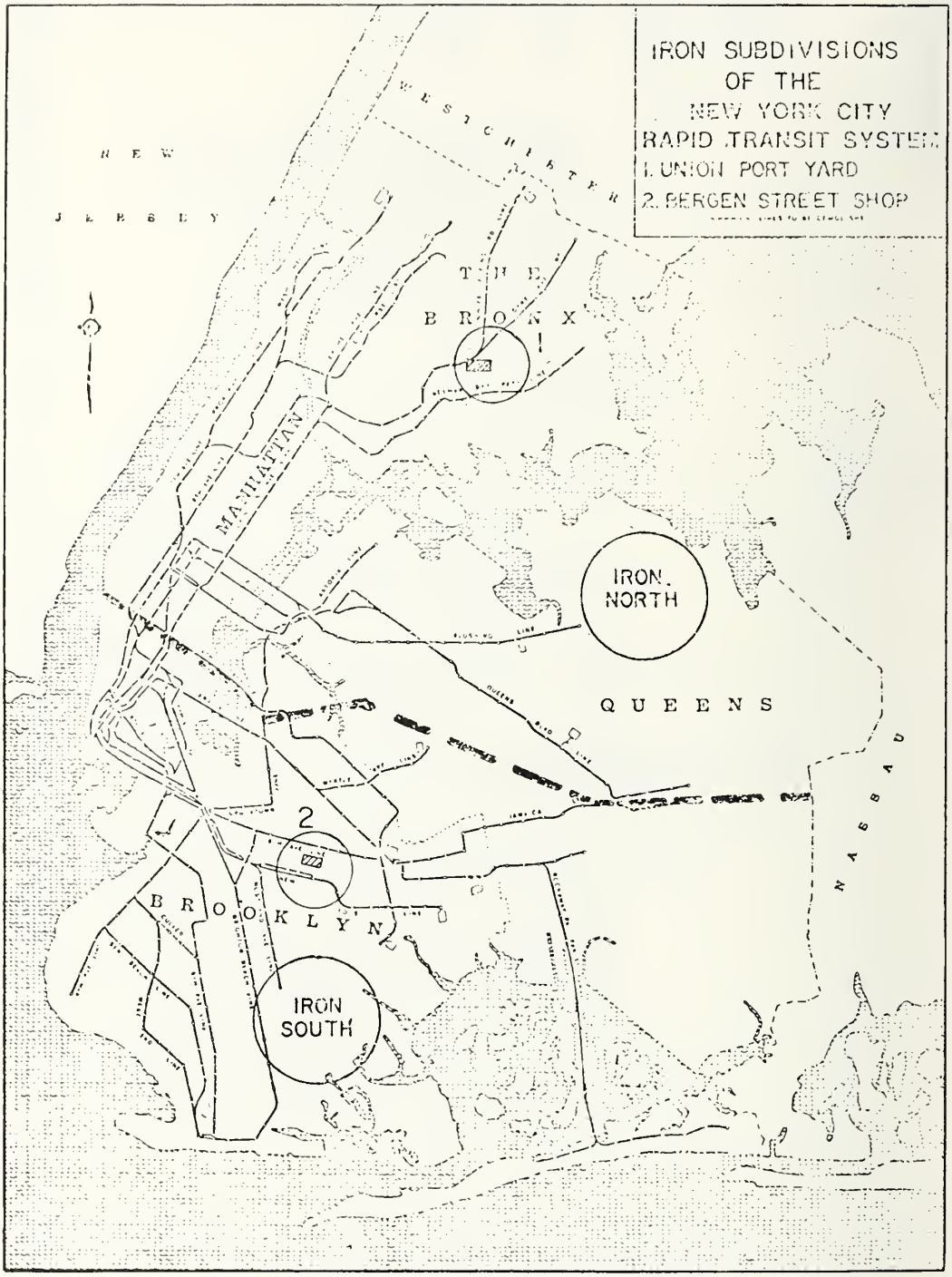


Figure 7-30. IRON WORKERS SUBGROUP

APPENDIX A

STATISTICAL INFORMATION ON SUBWAY SYSTEMS

	SYSTEM	ROUTE LENGTH TOTAL MILE	ROUTE LENGTH SUBWAY MILE	NUMBER OF LINES (BR=BRANCHES)	NUMBER OF STATIONS	AVERAGE STATION SPACING MILE	HISTORY START OPERATION	HISTORY PORTION AFTER 1945 (N=UNCERTAIN INFO)
		1	2	3	4	5	6a	6b
EUROPE	PARIS	154		19	321	0.46	1900	
	BERLIN(WEST)	55	44	8	95	0.48	1902	REBUILT & EXD
	HAMBURG	56	20	3	79	0.66	1906	(1/4 1973)
	MILAN	21	13	2	43	0.45	1964	100%
	BARCELONA	29	22	7	66	0.37	1926	72%
	MADRID	30 + 9 SUBURBAN	N* 30	6	82	0.34	1919	N 50%
	STOCKHOLM	43	16	2 + BR	72	0.50	1949	100%
	LONDON	252	99	7 + BR	279	0.80	1863	
	OSLO	18		1 + BR	35	0.51	1928	N 80%
	LENINGRAD	30		3	32	1.1	1955	100%
	MOSCOW	98		8	96	1.1	1935	75%
NORTH & SOUTH AMERICA	MONTREAL	16		3	26	0.50	1966	100%
	TORONTO	26	23	2	47	0.66	1954	100% 50%-57 30%-68
	BOSTON	39	20	3	44	0.60	N 1897	
	CHICAGO	89	10	7		0.70	N 1943	
	CLEVELAND	19	0.5	1 + BR	18		N 1900	IND-1930's
	NEW YORK CTA	232	137	30	462	0.5 1.4 (exprL)	N 1870	
	PHILADELPHIA	29	18	4	52	0.58	1908	
	SAN FRANCISCO	75	24	1 + BR	33	1.0	1972	N 100%
	MEXICO CITY	26	N 22	3	49	0.53	1967	100%
	BUENOS AIRES	20		5	57	0.38	1914	10%
JAPAN	NAGOYA	20		2	36	0.59	1945	100%
	OSAKA	41	N 25	6	54	0.70	1933	N 80%
	TOKYO	85		7	138	N 0.75 AUG 0.625	1925	N 85%

*N - APPROXIMATE

	SYSTEM	PASSENGER PER ANNUM (MILLIONS) RAPID TRANSIT RAILWAY	PASSENGER PER ANNUM (MILLIONS) TOTAL PUBLIC TRANSPORT	CAR-KM PER ANNUM (MILLIONS)	AVG. SPEED (INCL STOPS) MILE/HOUR	CAR CAPACITY MAXIMUM	CAR CAPACITY SEATED	ROLLING STOCK NUMBER OF CARS OWNED
		7	8	9	10	11a	11b	12
EUROPE	PARIS	1223		200	15 - 33	N 150		1930
	BERLIN (WEST)	271			18 - 21			774
	HAMBURG	190		55	18	121	31	854
	MILAN	121	489		18.6	210	35	219
	BARCELONA	241						256
	MADRID	595	1734	57				560
	STOCKHOLM	190		46	19.8	156	48	659
	LONDON	655	2068	350	20.3	155	36	4537
	OSLO	29	141		19.8	150	63	135
	LENINGRAD	483			24.5	170	40	
	MOSCOW	1770						
NORTH & SOUTH AMERICA	MONTREAL	125	270	33	20 - 32	160		345
	TORONTO	169	346	37	20	230,310	62,83	410
	BOSTON		159		N 20	180, 278	48, 72	353
	CHICAGO	99	372	868	N 24	100	48	1179
	CLEVELAND	13			30		52, 54	117
	NEW YORK	1178	1559	348	20 - 22	146	54	6800
	PHILADELPHIA	56	222	23	18	150, 190	56, 67	466
	SAN FRANCISCO	N 33			42		72	
	MEXICO CITY	550			32	160	38	537
	BUENOS AIRES	261				150 - 200		402
JAPAN	NAGOYA	179			20.4	115		
	OSAKA	700	959	55				625
	TOKYO	1300	2000		19.8	98 - 147 (AVG 170)	(AVG 53)	1342

SYSTEM	MAXIMUM NUMBER OF CARS PER TRAIN	LENGTH OF CAR FEET	WEIGHT OF CAR KIP	TRACK LINE GEOMETRY MAXIMUM GRADE %	TRACK LINE GEOMETRY MINIMUM CURVE (FEET)	EXCAV SHAPE METER	TUNNEL LINING METHOD, MATERIAL
	13	14	15	16	17	18a	18b
PARIS	4-9	49		4-3	246 - 479	0+6.3 Ø 8.7 6.2x3.6	MASONRY PC
BERLIN (WEST)	6-8	51		4	164 - 258	6.3x3.4	CAST IRON
HAMBURG	3-9	45		5	223 - 590	2x7.3-4.2	
MILAN	N 6	57.4	66			7.5x3.9	
BARCELONA	3-6	46-56	26-110			8.0x5.5	
MADRID	3-6	47		5	295	6.86x4.45 7.62x4.11	CONCR MASONRY BRICK
STOCKHOLM	8	57		4	656	7.6	
LONDON	4-8	53		3.3	330,1320	Ø365,3.81	CAST IRON PRECAST CONC
OSLO	6	56			656		
LENINGRAD	5	64				Ø5.1 etc 7.6x3.0	
MOSCOW	7	61	64	4	656	Ø-5.46	
MONTREAL	9	53		6.3	460	7.11x	CONC
TORONTO	6-8	57		3.45	400	8.87x4.06	CAST IRON
BOSTON	4	47-70				Ø6.20	CAST IRON
CHICAGO	8	48		3.5	265		
CLEVELAND		49-70					
NEW YORK	10-11	60		3	178	7.96x3.88	
PHILADELPHIA	6	56		5	105		
SAN FRANCISCO		70		4	500	[C&C-7.5M [TUNN-8.7 M	FABR STEEL
MEXICO CITY	9	52				7 x 4.9	PRECAST CONC
BUENOS AIRES			41-77	3	262	7.7x4.5 8.45x4.65	
NAGOYA	4-5	51	48	3.5	410		
OSAKA	5-8	61		3.5	393	Ø-5.7	
TOKYO	2-10	52-65	62-72			7.8x3.9	
					(AVG 404)		

	SYSTEM	CURRENT SUPPLY: COLLECTION (LEGEND SEE ABOVE) 19	CURRENT SUPPLY: VOLTAGE FROM SUB-STATION 20a
EUROPE	PARIS	LG13, 3RT,0+P	750DC
	BERLIN (WEST)	3RT, 3RB, 3RT	780DC
	HAMBURG	3RT, 4RT	750DC
	MILAN	0+P	750DC,1500DC
	BARCELONA	3RT, 0+P	1200-1500DC
	MADRID	0+P	600DC
	STOCKHOLM	3R	650DC
	LONDON	4R	600DC
	OSLO	3R	750DC
	LENINGRAD	3R	825DC
	MOSCOW	3R	825DC
NORTH & SOUTH AMERICA	MONTREAL	LGB	750DC
	TORONTO	3R	600DC
	BOSTON	3R, 0+P	600DC
	CHICAGO	3R,0+P	600DC
	CLEVELAND	PWM,0+P	600DC
	NEW YORK	3R	600DC
	PHILADELPHIA	3R	600DC
	SAN FRANCISCO	3R	1000DC
	MEXICO CITY	LGB	750DC
	BUENOS AIRES	3R, 0+P	1100/500/ 600/1600
JAPAN	NAGOYA	3R	600DC
	OSAKA	3R,0+P	750/1500
	TOKYO	3R,0+P	600/1500

LEGEND: (3RT = THIRD RAIL SYSTEM - TOP COLLECTION
(3RB = THIRD RAIL SYSTEM - BOTTOM COLLECTION
(LGB = LATERAL GUIDE BAR

0+P = OVERHEAD + PANTOGRAPH)
4RT = FOURTH RAIL SYSTEM)
PWM = PULSE WITH MODULATION)

APPENDIX B

GUIDELINES FOR EXISTING SUBWAY MAINTENANCE

Month ☐☐ Day ☐☐ Year ☐☐ File: R11

Inspector's Name _____

SUBJECT: TRACKWAY - CUT AND COVER
TRANSIT PROPERTY: _____
SECTION: _____

Field Sample
Sheet 1 of 5
Issue 9.22.75
Revision

	DATA	CODING	KEY PUNCH
	SYSTEM OF UNITS	ENGLISH [E] METRIC [M]	14 ☐
	UNIT OF CURRENCY	D MARK [D] FR FRANCS [F] LDS STERLING [L] US DOLLARS [S] JAP YEN [Y]	15 ☐
BASE DATA	GROUND TYPE	ROCK [R] GRAVEL [G] SAND [S] SILT [M] CLAY [C] OTHER [X] _____ FOR COMBINATION, ENTER 2nd TYPE IN COL 17	16 ☐ 17 ☐
	GROUND PERMEABILITY	ACTUAL (ENG: 10^{+}_{-nn} FT/YR) [±][n][n] (MET: 10^{-n} m/sec)	18 ☐☐☐
	GROUND WATER AVG ELEV BEL SURF SEAS FLUCTUATION	ACTUAL ☐☐ ACTUAL ± ☐☐	21 ☐☐ 23 ☐☐☐
	CHEM BAL OF SOIL+WATER DEGREE OF ACID/ALKALI	ACIDIC [A] BASIC [B] NEUTRAL [N] HIGH [H] MEDIUM [M] LOW [L]	26 ☐ 27 ☐
	WATER CONTROL DURING CONSTRUCTION DEEP WELLS PUMPING FROM BOTT LEV GROUTING OTHER	YES [Y] NO [N]	28 ☐ 29 ☐ 30 ☐ 31 ☐
	GROUND SUPPORT DURING EXCAVATION	EXCAVATION WITHOUT SUPP [A] SOLDIER PILES [B] SLURRY WALLS [C] SHEET PILES [D] SECANT WALLS [E] OTHER [X] _____ FOR COMBINATION ENTER 2nd TYPE IN COL 33	32 ☐ 33 ☐

	DATA		CODING	KEYPUNCH
BASE DATA (CONTD)	BACK FILL		GRAVEL [G] SAND [S] NATIVE MATERIAL [N] (FOR COMBINATION ENTER 2nd TYPE IN COL 35)	☐ ☐
	TYP	WALLS	CAST IN PLACE [C] SLURRY WALLS [M] SECANT WALLS [N] OTHER [X]	☐
		ROOF	CAST IN PLACE [C] PRECAST [P] OTHER [X]	☐
	FOUNDATION BASE		EXISTING GROUND PILES ☐ REPLACED GROUND ☐ OTHER ☐ ENTER COMB IN COL 39	☐ ☐
STRUCTURE	THICKNESS OF INVERT THICKNESS OF WALLS THICKNESS OF ROOF DIMENSION BETW WALLS DIM FLOOR TO CEILING		ACTUAL (ENG: in MET: cm) " " " " " " " " " " " "	☐☐☐ ☐☐☐ ☐☐☐ ☐☐☐☐☐ ☐☐☐☐
	TYPE OF SECTION		NUMBER OF SINGLE TRACK UNITS NUMBER OF DOUBLE TRACK UNITS NUMBER OF TRIPLE TRACK UNITS	☐ ☐ ☐
	DESIGN PHILOSPHY		COMPLETELY WATERTIGHT [T] DRAINAGE WALLS [W] DRAINAGE INVERT [I] DRAINAGE PROVISIONAL ONLY [P] OTHER [X]	☐
	WATERPROOF MEMBRANE		BENTONITE [B] RUBBER [R] PLASTIC ☐ BUILTUP 3-PLY [A] 4-PLY [C] 5-PLY [D] MASTIC [M] OTHER ☐ THICKNESS OF MEMBR (ENG:1/32 inch MET: mm)	☐ ☐☐
	EXTENT OF COVER		ROOF [R] PARTIAL TANK [P] COMPLETE TANK [C] IF PARTIAL TANK: DIST BELOW ROOF (ENG: FT. MET: CM)	☐ ☐☐☐☐

	DATA	CODING	KEYPUNCH
CONSTRUCTION JOINTS	POSITION	WALL BOTTOM [B] WALL TOP [T]	☐
	JOINT TYP	T+G [T] LAP [L] OTHER [X]	☐
	WATER STOP WIDTH	ACTUAL (ENG: IN MET: CM)	☐☐
	PREPARATION	WIRE BRUSH GREEN [W] ROUGH [R] MORTAR [M] HACK [H] OTHER [X] _____	☐
	HACK %	ACTUAL %	☐☐
	OVERALL WORKMANSHIP	GOOD [G] FAIR [F] POOR [P]	☐
EXPANSION JOINTS	TYPE	CHEVRON [C] PLATE [P] EXTERNAL [E] OTHER [X] _____	☐
	WIDTH	ACTUAL (ENG: IN MET: CM)	☐☐
	SPACING IN ROOF	ACTUAL (ENG: FT MET: M)	☐☐
	SPACING IN WALLS	" " "	☐☐
	SPACING IN FLOOR/INVERT	" " "	☐☐
	DISPLACEMENT	ACTUAL (ENG 1/10 in MET: mm)	☐☐
	SPALLING & CRACKING	SEVERE [S] MODERATE [M] LOW [L]	☐
	OVERALL WORKMANSHIP	GOOD [ ] FAIR [ ] POOR [ ]	☐
CONTRACTION JOINTS	DETAIL	NOTCH REBAR THROUGH [N] REBAR SLIP [S] DOWEL [D] OTHER [X] _____	☐
	WATERPROOF SYSTEM	FULL MEMBRANE [F] WATERSTOP [W] BENTONITE STRIP [B] CAULK MATERIAL [C] NONE [N] OTHER [X] _____	☐
	WIDTH OF BENTONITE STRIP	ACTUAL (ENG: IN MET: CM)	☐☐
	SPACING IN ROOF	ACTUAL (ENG: FT MET: M)	☐☐
	SPACING IN WALLS	ACTUAL (ENG: FT MET: M)	☐☐
	SPACING IN FLOOR/INVERT	" " "	☐☐
	DISPLACEMENT	ACTUAL (ENG: 1/10 in MET: mm)	☐☐
	OVERALL WORKMANSHIP	GOOD [G] FAIR [F] POOR [P]	☐
CRACKS	AVG LENGTH	ACTUAL (ENG: FT MET: M)	☐☐
	AVG WIDTH	ACTUAL (ENG: 1/100in MET: mm)	☐☐
	AVG SPACING IN ROOF	" " FT " m)	☐☐
	AVG SPACING IN WALLS	" " " ")	☐☐
	AVG SPACING IN INVERT	" " " ")	☐☐

	DATA	CODING	KEYPUNCH
CONSTRUCTION QUALITY	GRADE CONCRETE CYLINDER STRENGTH	ACTUAL: ENG: LBS/SQ IN MET: KG/CM^2	1 ☐☐☐☐
	MAX TEMPERATURE OF CONCRETE DURING POURING SPECIFIED	YES [Y] NO [N] INFORMATION UNAVAILABLE [U]	☐
		IF YES: DEGREES (F: C°)	☐☐
	WHEN AMBIENT TEMPERATURE DURING POURING SPECIFIED	YES ☐ NO ☐ INFORMATION UNAVAILABLE ☐	☐
		IF YES: DEGREES (F:C^O)	☐☐
	AIR ENTRAINING AGENT	SPECIFY %	7 ☐☐
	ADDITIVES	ACCEL [A] RETARDER [R]	9 ☐
	TYPE OF CEMENT	QUICK SET [Q] STD [S] LOW HEAT [L]	10 ☐
	CURING METHOD	PLASTIC COMPOUND [P] WATER SPRAY [W] WET SACKING [S] OTHER [X]	11 ☐
	CURING TIMES	ACTUAL DAYS	12 ☐☐
	DAMAGE	DETERIORATION ☐ SPALLING [S] CORROSION [C] OTHER [X]	14 ☐
		FOR COMB. ENTER 2nd IN COL 15	15 ☐
	DEGREE OF LEAKAGE: CONSTRUCTION JOINTS EXPANSION JOINTS CONTRACTION JOINTS	SEVERE [S] MODERATE [M] LOW [L] " " " " " "	16 ☐ 17 ☐ 18 ☐
PERFORMANCE	WHEN LEAKAGE WORST: CONSTRUCTION JOINTS EXPANSION JOINTS CONTRACTION JOINTS	SUM [S] WINT [W] DURING RAIN [R] " " " " " "	19 ☐ 20 ☐ 21 ☐
	REMEDIAL ACTION FOR: CONSTRUCTION JOINTS EXPANSION JOINTS CONTRACTION JOINTS	LET RUN [R] CANALIZED [C] ASBESTOS CAULKING [A] THIOKOL CAULKING [T] EPOXY INJECTION [E] AM 9 INJECTION [9] BENTONITE JOINT [J] BENTONITE BEHIND JOINT [B] OTHER [X] IF VARIOUS, ENTER IN SEQUENCE	22 ☐ 23 ☐ 24 ☐
	SETTLEMENT	UNEVEN SETTLEMENT VERT. DIST PER 100m (328 FT) (ENG: INCH MET: CM)	25 ☐☐

CUT & COVER

SHEET 5 OF 5

	DATA	CODING	KEYPUNCH
COST	INSTALLATION: TOTAL	ACTUAL (THOUSANDS)	27
	MAINTENANCE		
	TOTAL ANNUAL	" "	32
	LABOR	" "	36
	MATERIAL	" "	40
	EQUIPMENT	" "	44

APPENDIX C

GENERAL INDEX FOR ITEMS AND ITEM TYPES
(ITEM = XX., ITEM TYPE = .X)
F8

0. FINISHES (Form F1, F5 F6)

1. FLOOR
   - 1.1 Terrazo
   - 1.2 Concrete
   - 1.3 Marble
   - 1.4 Quarry Tile
   - 1.5 Brick

2. STAIRS
   - 2.1 Brick
   - 2.2 Concrete
   - 2.3 Marble
   - 2.4 Tile

3. WALLS
   - 3.1 Dome Tile
   - 3.2 Ceramic Tile-Epoxy Base
   - 3.3 Ceramic Tile-Cement Base
   - 3.4 Stainless Steel
   - 3.5 Glass

4. CEILINGS
   - 4.1 Plaster (Sand, Lime, Cement)
   - 4.2 Plaster (Gypsum)
   - 4.3 Horiz. Acoustic Material
   - 4.4 Acoustic Baffles

5. SKYLIGHTS, GLASS PANELS
   - 5.1 Glass
   - 5.2 Plastic

10. EQUIPMENT (Form F1, F5, F6)

11. LIGHTING FIXTURES
   - 11.1 Incandescent
   - 11.2 Fluorescent

12. PUMPS

13. FANS
   - 13.1 Line Ventilation Fans
   - 13.2 Station Fans

14. ESCALATORS
   - 14.1 Indoor-Variable control
   - 14.2 Indoor-continuous
   - 14.3 Outdoor-Variable control
   - 14.4 Outdoor-continuous

15. ELEVATORS
   - 15.1 Electric
   - 15.2 Hydraulic

16. INSULATORS FOR THIRD RAIL
   - 16.1 Porcelain
   - 16.2 Glass
   - 16.3 Plastic

20. UNDERGROUND STRUCTURE (Form F1, F5, F7)

21. CUT AND COVER, SUBWAY

22. CUT AND COVER, STATION

23. DRIVEN TUNNEL, SEGMENTED LINING

24. DRIVEN TUNNEL, CAST IN PLACE LINING

25. DRIVEN TUNNEL SHOT-CRETE LINING, NO LINING, ROCK BOLTS.

26. VENTILATION SHAFTS

30. OTHER INFORMATION (Form F1, F5,F7)

31. GENERAL INFORMATION

32. ENVIRONMENT (DUST & AIR)

33. ACCIDENTS AND CLAIMS

INDEX OF FORMS 1,5,6,7,8,9

F9

Form No.	Heading	Label on the form	
		English	German
1	-Data Sheet	F1	
5	-Instruction for data sheet	F5	FG5
6	-Checklist for comments with respect to the item		
	- Floor	F6.1	FG6.1
	- Stairs	F6.2	
	- Walls	F6.3	
	- Ceilings	F6.4	
	-Skylights, Glass panels	F6.5	
	-Lighting Fixtures	F6.11	
	- Pumps	F6.12	
	- Fans	F6.13	
	- Escalators	F6.14	
	- Elevators	F6.15	
	- Insulators for third rail	F6.16	
7	Data Gathering Sheet		
	- Cut and Cover, Subway/ Station	F7.21/22	
	- Driven Tunnel, Segmented Lining	F7.23	
	- Driven Tunnel, Cast in Place Lining	F7.24	
	- Driven Tunnel, Shot-Crete Lining, No Lining, Rock Bolts.	F7.25	
	- General Information	F7.31	
	- Enivronment (Dust & Air)	F7.32	
	- Accidents and Claims	F7.33	
8	- General Index for Items and Item Types	F8	FG8
9	- Index of Forms 1,5,6,7,8,9	F9	

DATA SHEET F1

Guidelines for subway maintenance.
A study sponsored by US Department of Transportation.

Item (1)

Item Type (2)

Transit Authority (3)_____ Date (4)_____ Name(5) _____

Location within the system (6)_____

_____ Year installed (7)_____

_____ _____ X _____ = _____

Quantity (8) Unit (9) Original cost/Unit (10) Total original cost (11)

Activity (12)	Cost-Group (13)	Frequency (14)	Unit (15)	Units per year or occasion (16)	Cost per Cost Group Unit (17)	Cost per year (18)

Comments: (19) - Headings: 1) Description, 2) Performance, 3) Causes of deterioration, 4) Upkeep, 5) Improved Design, 6) Other points .

For additional space turn page

INSTRUCTIONS FOR DATA SHEET F5

(Numbering refers to heading numbers on the data sheet)

1. ITEM: One of the following

		UNITS Metric	Eng.
0	Finishes		
	1 - Floors	m^2	Ft^2
	2 - Stairs	m_2	Ft_2
	3 - Walls	m^2	Ft^2
	4 - Ceilings	m^2	Ft^2
	5 - Skylights, Glass Panels	m^2	Ft^2
10	Equipment		
	11 - Lights - (Unit = Illuminated Area)	m^2	Ft^2
	12 - Pumps - (Unit = No. of sumps)	Number	Number
	13 - Fans - (Volume of subway space)	m^3	Ft^3
	14 - Escalators	Number	Number
	15 - Elevators	Number	Number
	16 - Insulators holding third rail.	Number	Number
20	Underground Structures		
	21 - Cut and Cover, Subway	m_3	Ft_3
	22 - Cut and Cover, Station	m^3	Ft^3
	23 - Driven tunnels, Cast in place lining	m	Ft
	24 - Driven tunnels, segmented lining	m	Ft
	25 - Driven tunnels, shot-crete	m	Ft
	26 - Ventilation Shaft	m	Ft

2. ITEM TYPE: The items are sub-divided according to type. Example: "Floor" types would include terrazzo, concrete, marble, quarry tile.

3. TRANSIT AUTHORITY: Abbreviation is sufficient.

4. DATE: Date of completing form data.

5. NAME: Name of the person within transit authority responsible for completing data.

6. LOCATION WITHIN THE SYSTEM: Identification of locations of specific quantity.
Example: 3000 m^2 on each of the stations S_1,S_2 and S_3 on line L_4.
Abbreviations refer to key on standard system layouts.

7. YEAR INSTALLED: The year the item was put in service.

8. QUANTITY: Quantity of the units shown in 9.

9. UNIT According to instruction 1 "item".

10. ORIGINAL COST/UNIT: The total installment cost in local currency at the time of installment.

11. TOTAL ORIGINAL COST (8) x (10)

12. ACTIVITY: Legend J = Janitorial
M = Maintenance
R = Replacement

All activities related to the item should be identified.
Example: Floor: Inspection, sweeping, polishing, repair, replacement etc.

13. COST GROUPS: Legend

L = Labor (hour, days, month)
E = Equipment (hour, days, month)
M = Material (Ft, Ft^2, etc.)
P = Energy (KWH, etc.)
S = Subcontractor ($)
C = Claims- payments to patrons & related expenses ($)
O = Overhead ($)
X = Other specify ($ etc.)
Y = Other specify ($ etc.)
Z = Other specify ($ etc.)

All cost groups related to the activity should be included

14. FREQUENCY

a) For cycles one year or less mark "1".
b) For cycles longer than one year, mark the number of year.
Example: Repainting every 6 year - mark 6.

15. COST GROUP UNIT Can vary. See note 13.

16. UNITS PER YEAR OR OCCASION. Yearly quantity or (if activity less frequent than one year) quantity per occasion.

17. COST PER COST GROUP UNIT Actual cost in local currency.

18. COST PER YEAR: For items with cycles within a year = (16) x (17). For other items the present worth of the cost is calculated after a discount factor is chosen (will be made later by Bechtel).

19. COMMENTS: Comments to be numbered according to the checklist for the item. (See separate set of checklists) For additional space turn page.

CHECKLIST FOR COMMENTS WITH RESPECT

TO THE ITEM
F6:1

1. FLOOR

IN GENERAL	SPECIFICALLY
1. DESCRIPTION: Manufacturer, identification, measures, material, finish, joints, sub-components, method of installation, adjacent components.	Base Material
2. PERFORMANCE: Condition: satisfactory or not, slippery, leakage, breakdowns, DETERIORATION: spalling, cracks, cavities, dust collection.	
3. CAUSES OF DETERIORATION: Wear, dust, dirt, humidity, water, temperature, wind pressure, corrosion, chemicals, acidic/alcalic, settlement, vandalism, poor design or installation.	Annual passenger frequency per unit area (M^2 or Ft^2) of station
4. UPKEEP: Janitorial, maintenance, replacement, cycles of upkeep, methods, equipments, tools, organization, crew composition, subcontractor. Inspection	Sweeping method (hand, mechanical) Washing method (hand, mechanical) Frequency of sweeping, washing
5. IMPROVED DESIGN: Suggestions and concepts to facilitate janitorial, maintenance and renewal activities. How to improve performance and avoid causes of damage.	
6. OTHER POINTS: Other points of interest with respect to design, construction, performance and renewal.	

GUIDELINES FOR EXISTING SUBWAY MAINTENANCE F7:21/22
DATA GATHERING
SHEETS ITEM: CUT AND COVER

Name Date Transit System

C-8 BASE DATA

HEAD	DATA REQUIRED	CODING	SECTION NR			
	Ground type	Rock R, Gravel G, Sand S, Silt M, Clay C Other X _____ For combination, enter 2nd type				
	Ground permeability	Actual (Eng. $10^{\pm nn}$ ft/year) (Met: 10^{-n} m/sec)				
	Ground water Avg. elev. below surface	Actual				
	Seasonal fluctuation	Actual $\pm$				
	Chem.bal of soil + water	Acidic A, Basic B, Neutral N.				
	Degree of acid/alkali	High H, Medium M, Low L.				
	Water control during construction					
	Deep wells	Yes Y, No N.				
	Pumping from bott. lev.	Yes Y, No N.				
	Grouting	Yes Y, No N.				
	Other _____	Yes Y, No N.				
	Ground support during excavation	Excavation without support A, soldier piles B, slurry walls C, sheet piles D, Secant walls E Other X _____ For combination enter 2nd type				
	Back fill	Gravel G, Sand S, Native material N, (for combination enter 2nd type				

DATA GATHERING SHEETS ITEM: CUT AND COVER

Name Date Transit System

HEAD	DATA REQUIRED	CODING	SECTION NR			
Structure C-9	Type of walls	Cast in place C, Slurry walls M Secant walls N, Other X_____				
	Type of roof	Cast in place C, Precast P, Other X_____				
	Foundation base	Existing ground E, Piles P, Replaced ground R, Other X _____				
	Thickness of invert	Actual (Eng: In Met: Cm)				
	Thickness of walls	Actual (Eng: In Met: Cm)				
	Thickness of roof	Actual (Eng: In Met: Cm)				
	Dimension between walls	Actual (Eng: In Met: Cm)				
	Dimension between floor to ceiling	Actual (Eng: In Met: Cm)				
	Type of section	Number of single track units				
		Number of double track units				
		Number of Triple track units				
	Design philosophy	Completely water tight T, Drainage walls W, Drainage invert I, Drainage provisional only P, Other X _____				
	Waterproof membrane	Bentonite B, Rubber R, Plastic P, Builtup 3-ply A, 4-ply C, 5-ply D, Mastic M, Other X _____				
		Thickness of membrane (Eng 1/32 inch, Met mm)				
	Extent of cover	Roof R, Partial tank P, Complete tank C, (indicate on enclosed figure)				

GUIDELINES FOR EXISTING SUBWAY MAINTENANCE F7: 21/22
DATA GATHERING
SHEETS ITEM: CUT AND COVER

Name Date Transit System

HEAD	DATA REQUIRED	CODING	SECTION NR			
STRUC-TURE		if partial tank: Dist. below roof (Eng: ft. Met: Cm)				
CONSTRUCTION JOINTS	Joint type	T+G T, Lap L, Other X _____				
	Water stop width	Actual (Eng: In Met: Cm)				
	Preparation	Wire Brush green W, Rough R, Mortar M, Hack H, Other X _____				
	Hack %	Actual %				
	Overall workmanship	Good G, Fair F, Poor P.				
EXPANSION JOINTS C-10	Type	Chevron C, Plate P, External E, Other X _____				
	Material	PVC P, Copper C, Bentonite B Other X _____				
	Width	Actual (Eng: In Met: Cm)				
	Spacing in roof	Actual (Eng: Ft , Met: m)				
	Spacing in walls	Actual (Eng: Ft , Met: m)				
	Spacing in floor/invent	Actual (Eng: Ft , Met: m)				
	Displacement	Actual (Eng: 1/10 in, Met: mm)				
	Spalling + Cracking	Severe S, Moderate M, Low L.				
	Overall workmanship	Good G, Fair F, Poor P.				
CONTR. JOINTS	Detail	Notch rebar through N, Rebar slip S, Dowel D. Other X _____				

GUIDELINES FOR EXISTING SUBWAY MAINTENANCE F7: 21/22
DATA GATHERING
SHEETS ITEM: CUT AND COVER

Name Date Transit System

HEAD	DATA REQUIRED	CODING	SECTION NR			
CONTRACTION JOINTS	Water proof system.	Full membrane F, Water stop W, Bentonite strip B, Caulk material C, None N. Other X _____				
	Width of bentonite strip	Actual (Eng: In Met: Cm)				
	Spacing in roof	Actual (Eng: Ft Met: M)				
	Spacing in walls	Actual (Eng: Ft Met: m)				
	Spacing in floor/invert	Actual (Eng: Ft Met: m)				
	Displacement	Actual (Eng: 1/10 in Met: mm)				
	Overall workmanship	Good G, Fair F, Poor P				
CONSTRUCTION QUALITY	Avg. length	Actual (Eng: Ft Met: m)				
	Avg. width	Actual (Eng: 1/100 in Met: mm)				
	Avg. spacing in roof	Actual (Eng: Ft Met: m)				
	Avg. spacing in walls	Actual (Eng: Ft Met: m)				
	Avg. spacing in invert	Actual (Eng: Ft Met: m)				
	Grade concrete	Actual (Eng: lbs/sq. in Met: kg/cm^2)				
	Where temperature of concrete during Pouring specified ?	Yes Y, No N, Information unavailable U				
		If yes: Degrees (F : C^o)				
	Where ambient temperature during pouring specified	Yes Y, No N, Information unavailable U				
		If yes: Degrees (F : C^o)				
	Air entraining agent	Specify %				
	Additives	Accel A, Retader R				

DATA GATHERING SHEETS ITEM: CUT AND COVER

Name Date Transit System

HEAD	DATA REQUIRED	CODING	SECTION NR			
	Type of cement	Quick set Q, Std S, Low heat L.				
	Curing method	Plastic compound P, Water spray W, Wet sacking S, Other X _____				
	Curing time	Actual Days				
PERFORMANCE	Damage	Deterioration D, Spalling S, Corrosion C, Other X _____ For combination enter 2nd				
	Degree of leakage: Construction joints	Severe S, Moderate M, Low L				
	Expansion joints	Severe S, Moderate M, Low L				
	Contraction joints	Severe S, Moderate M, Low L				
	When leakage worst: Construction joints	Sum. S, Wint. W, During rain R				
	Expansion joints	Sum. S, Wint. W, During rain R				
	Contraction joints	Sum. S, Wint. W, During rain R				
	Remedial action for: Construction joints	Let run R, Canalized C, Asbestos caulking A, Thiokol caulking T, Epoxy injection E, AM 9 injection 9, Bentonite joint J, Bentonite behind joint B, Other X _____ If various, enter in sequence				
	Expansion joints					
	Contraction joints					
	Settlement	Uneven settlement Vert. distance per 100 m (328ft) (Eng: inch Met: cm)				

Appendix D

CONCRETE FOR DURABILITY

The following text is a summary of two reports by Frank Joyce, Research and Engineering, Bechtel Corporation: "Material Requirements, Reinforced Concrete Subway," April 16, 1976, and a supplementary report, June 9, 1976.

MODES OF DETERIORATION

Indications of deterioration of reinforced concrete in subway structures normally include cracks, spalling, corrosion of the reinforcing bars, chemical attack, and mechanical damage.

Cracks arise from shrinkage during hydration or flexture tensile stresses. If the loads conform to conservative design assumptions and the shrinkage reinforcement is adequate, the cracks normally are not detrimental.

Spalling of concrete can occur from freeze thaw, honeycomb, or from improper form stripping. The rust from rebar corrosion exerts pressure on the concrete that may also result in spalling.

Cracks extending through a subway structure may permit water to seep through the concrete and leach out the protective alkali environment, thus permitting the rebar to corrode. Acids or chlorides in the water and stray currents can also accelerate the deterioration on rebars. Water containing high concentrations of sulphates may also attack the concrete on the exposed surface. Mechanical damage of the concrete may also occur in a transit subway structure due to derailment, fire, etc.

These modes of deterioration are all affected by the quality of the materials of the reinforced concrete, its composition, and workmanship. Below some of the key points in making durable concrete are described.

MATERIALS

Structures underground, particularly if constructed in filled ground, in swampy or in harbor areas, may be subject to attack from acids, organic substances, sewage, manufactured chemicals, or other agents that aggressively attack concrete. Soil borings along the right-of-way should be carefully analyzed for any unusual conditions that may cause deterioration, and the appropriate action should be taken during the design to protect the structure against attack.

Sulphate Soils and Waters

A primary chemical attack on cement below grade is from natural sulphate soils and waters (Ref. 1). Sulphate bearing soils are common in many areas and groundwater may also contain high concentrations of soluble salts. Structures exposed to sea water are subject to sulphate concentrations of about 2,600 ppm.

It is recommended that sulphate-resisting cements be used for all areas with appreciable amounts of sulphate. ACI recommendations (Ref. 2) are that concrete for use in soils containing from 0.10 to 0.20 percent water soluble sulphate (such as SO_4^-) should use cement containing not more than 8 percent tricalcium aluminate (ASTM C-150, Type II). When the concentration of water soluble sulphate in soil samples exceeds 0.20 percent, or when the sulphate solution contains more than 1,000 ppm, the tricalcium aluminate content of the cement should be limited to 5 percent (ASTM C-150, Type V.) These ACI recommendations are for conventional structures, with an estimated 30 to 60 year life, and should be considered as a minimum for a 150 year service life.

Some research (Ref. 3) has been performed on cement-pozzolan combinations to improve on sulphate resistance. Certain possolans had beneficial effects and others did not improve the sulphate-resisting quality of good cements. If cement with a low tricalcium content is not readily available, laboratory studies should be performed to determine the effectiveness of cement-pozzolan combinations, before use in high sulfate areas.

Non-Reactive Aggregates

Aggregates that react when exposed to cement are found in many areas of the United States (Ref. 4). This expansive reaction between the constituents of some aggregates and alkalies from cement has caused severe distress to many structures. The alkali aggregate reaction may not be visible for many years in a buried structure, as spalling might initially start at the soil interface where moisture is readily available.

Aggregates for long service life should be carefully tested for reactivity. Standard tests (Ref. 5) are available for evaluation of materials and concrete. In addition, a condition survey (Ref. 6) should be made to assess the service of existing structures previously constructed using any questionable aggregate-cement combination.

In areas where non-reactive aggregates are economically unavailable, laboratory tests should be performed to select the optimum aggregates and cements. Low alkali cements should be used and the addition of a good quality pozzolan has been found effective in reducing expansive reactions (Ref. 7).

Chloride Additives

The presence of chloride ions within concrete has been found to accelerate corrosion of embedded metals. The use of calcium chloride as a cold

weather accelerator or a component of admixtures should be prohibited. In addition, water sources should be evaluated to find a reasonably low chloride mix water. The total chlorides in the concrete mix should be as low as practicable; however, in no case should the total chlorides, including any found in the aggregates, exceed one third pound per cubic yard.

Chloride Ions

Chloride ions from external sources will not chemically attack concrete but may corrode reinforcement or other embedded steel if the concrete is sufficiently cracked or permeable. The permeability of a low water-cement ratio concrete may be sufficiently low to provide long-term protection against corrosion of reinforcing steel in structures in salt water. However, if severe cracking is anticipated, supplementary protection of the steel, such as coatings or cathodic protection, should be provided.

A good water reducing-set retarding admixture meeting ASTM C494, Chemical Admixtures for Concrete, Type D (Ref. 5) can be used to improve the workability of concrete (Ref. 8). Air entrainment is also an aid to better workability, and both these admixtures, by reducing the water-cement ratio, reduce the set shrinks of concrete, and consequently the incidence of cracking. Workability admixtures free from chlorides do not affect the durability of concrete.

PROPORTIONING, MIXING, PLACING, AND CURING

Low Water-Cement Ratio

The available long-term studies indicate that concrete made with a low water-cement ratio has a minimum loss in strength after 10 years and in most cases increases in strength up to 50 years. A low water-cement

ratio is also beneficial for sulfate resistance and creates a more impermeable concrete. A recommended value for water-cement ratio is 0.40 to 0.45. This should produce approximately 5,000 psi concrete.

Entrained air may be required for construction of subway structures in cold climates. After backfilling is complete, exposure to freeze-thaw will not be a design consideration; however, use of entrained air is recommended for better concrete workability and impermeability even in mild climates.

Concrete Placing and Curing Practices

Durability of concrete is dependent upon the mixing, placing, curing, and finishing of the concrete. Concrete produced and placed with the good practices defined in various ACI standards should be capable of providing a service life of 150 years. Specific attention should be given to placing, vibration, and curing. Specifications should include provisions for preventing segregation, proper vibration during placing, and water curing for 14 days. These specifications must be enforced by adequate inspection.

Temperature at Concrete Set

Temperature at concrete set is an important factor in the cracking of concrete, as thermal cracking is induced by the differential between the temperature at concrete set and the temperature of the completed structure. The temperature rise of concrete during set and curing is due to the chemical reaction of the cement (heat of hydration). During heat generation, there is also a heat dissipation into ambient air. These two processes occur simultaneously.

The temperature at the interior of placed concrete is dependent upon the following variables:

Type of cement,
Amount of cement,
Thermal diffusion,
Admixtures,
Ambient temperature,
Type of curing,
Form material, and
Geometry or mass of placement.

Examples are given below for approximate concrete final set temperatures and placing temperatures in the center of a 2-foot thick wall. The concrete is assumed to be made with six sacks of Type II cement, with aggregate of 1.0 ft^2/day thermal diffusively, and with no admixtures. Steel forms are assumed on both sides of the wall and ambient temperatures of $70^{o}F$ are assumed. On this basis, heat transfer calculations using the Schmidt Method (Ref. 9) indicate that the center of wall temperatures would be:

Placing Temperature F^{o}	Maximum Temperature at Set F^{o}
50^{o}	98^{o}
70^{o}	101^{o}
80^{o}	106^{o}

The peak temperature in all cases would occur four to five hours after placing. The peaks would be appreciably higher if the concrete were placed against wood lagging on the earth face or if timber forms were used. These would retard the surface heat dissipation.

If the temperature of the concrete structure stabilized after some months at $65^{o}F$, the temperature differential generating thermal cracks would be

about 35°F. Internal temperatures of concrete can readily reach 130° to 140°F for 3- or 4-foot thick walls.

Temperature as a Function of Cement Type

The heat of hydration of cement is also a variable dependent upon the type of cement used. ASTM C-150, Portland Cement, includes optional requirements for low heat of hydration for Type II, II A, and IV cements. Cement for mass concrete should have a low heat of hydration. Typical comparative values are presented below:

Cement Type	Total Heat of Hydration (Calories per Gram)			
	1 day	3 days	7 days	28 days
I	52	79	87	92
II	42	64	75	82
III	76	102	108	164
IV	28	45	52	65
V	32	49	57	69

Admixtures Effect on Temperature

Water-reducing and set-retarding admixtures may be used in concrete to reduce the cement proportion, to provide a longer set time, and to improve workability (Ref. 8). The lower cement content (approximately 1/2 sack) would lower the total heat of hydration to achieve a cooler concrete. The set retardation may allow the peak hydration temperatures to occur later in the day when cooler ambient air is available to better dissipate heat.

Curing Compounds

Water spray is more effective than membrane curing compounds in reducing the temperature of concrete during set (Ref. 9). It is

particularly effective when steel forms are used, as heat can be dissipated from the concrete more readily during set.

Drying Shrinkage in Concrete

The quality of aggregates, ratio of coarse aggregates to fine aggregates, type of cement, and W.C. Ratio are controllable factors in shrinkage and creep (Ref. 10).

The quality of aggregate directly affects the drying shrinkage characteristics of concrete. Concrete made with competent rock, such as crushed limestone or granite, will generally have less shrinkage than concrete made with softer shale or river gravels. Concrete made with a high proportion of coarse aggregate to sand will generally have less drying shrinkage than concrete made with a lower proportion of coarse aggregate to sand. Minor changes in gradation of coarse aggregates or sand will also slightly affect drying shrinkage, especially if the amount of fines increases.

Type II cement may have a slightly lower shrinkage than either Type I or III. In addition, some regional brands of Type II cement may be somewhat lower in shrinkage characteristics than others. The shrinkage properties of cement are dependent upon the unique quarry of origin and typically not all cement produced by a major manufacturer could be considered to be low shrinkage. Types IV and V are specialty cements, and the drying shrinkage characteristics should be evaluated on an individual manufacture basis.

Concrete may be classified as low drying shrinkage with test results of less than 400 millionths of an inch shrinkage at one year of age and as high drying shrinkage testing over 600 millionths of an inch shrinkage at one year of age. Special structural details should be used to minimize cracking if concrete with high drying shrinkage is used for subway construction.

Corrosion of Reinforced Steel

Rebar corrosion results from continuing attack by chloride ions in a less basic environment than exists in normal concrete (Ref. 11). Generally, thermal shrinkage or flexure cracks permit ground water to penetrate the concrete and attack the rebar. If cracks are sealed either by self-healing or by external methods, the possibility of corrosion is substantially reduced.

Cracks up to 0.005 inch in width at the exposed surface are generally self-sealing in a typical groundwater environment if the crack is stable (Ref. 12). If the crack is unstable, due to shifting live loads or creep, it will probably not be self-sealing.

Cracks larger than 0.002 inch in width at the exposed surface can be sealed using epoxy pressure grouting techniques if the surface is properly exposed. Cracks larger than 0.02 inch in width at the exposed surface can be sealed using conventional concrete grouting techniques.

REFERENCES

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3. Polivka, M. and E. H. Brown; Influence of Various Factors on Sulphate Resistance of Concretes Containing Pozzalan; ASTM Proceedings Vol. 58.

4. Mielenz, R. C.; Petrographic Examination of Concrete Aggregate; ASTM Proceedings Vol. 54.

5. ASTM, Part 14.

6. ACI Committee 201; Guide for Making a Condition Survey of Concrete in Service; ACI Manual of Standard Practice.

7. Pepper, C. and B. Mather; Effectiveness of Mineral Admixtures in Preventing Excessive Expansion Due to Alkali-Aggregate Reaction; ASTM Proceedings Vol. 59.

8. ACI 212, Guide for Use of Admixtures in Concrete.

9. ACI 207, Mass Concrete for Dams.

10. PCA Design and Control of Concrete Mixtures.

11. ACI SP-49-5, Corrosion of Metals in Concrete.

12. ACI 207, Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete.

Appendix E

WATERPROOFING AND SEALANTS

The following is a summary of reports by Theadore Gilbert of Research and Engineering, Bechtel Corporation.

Interaction of the environment with waterproofing and protective material determines how long a material will last. Buried structures coated with coal tar pitch have been recovered intact after 100 years, but coal tar pitch in the sunlight oxidizes and cracks in a short time. Technology has been and is being developed to reduce the adverse interaction of protective materials with environmental factors to extend the possible life of materials to 150 years or more.

DEGRADATION OF ORGANIC MATERIALS

Many different factors case deterioration of organic materials, including extremes of temperature, changes in temperature, chemical reactions, microbiological reactions, the presence of oxygen or sunlight, soil movement, and water seepage. Seldom does one factor alone cause the deterioration of a material, although elimination of one causitive factor may extend the life of that material.

Lack of sunlight can produce microbiological problems. In buried structures, enzymes carried in groundwaters can be destructive. Ground that goes through cycles of alternately high and low temperatures, with attendant freezing and thawing, creates water seepage problems. Ground movement at very low temperatures ($-40^{\circ}F$) may cause cracking, as may great changes in temperature, such as from below freezing to $150^{\circ}F$.

These changes might also dislodge a seal or disfigure a structure. Bacteria, fungi, and other forms of life found in the soil may also damage an organic covering.

The presence of oxygen may cause embrittlement and loss of mechanical strength, usually under the influence of photo radiation. But even without sunlight, polyethylene and polypropylene are rapidly oxidized at $60^{\circ}C$. Embrittlement can also be caused by stress reactions, such as compaction of the soil.

Soil movement resulting in soil stress can rip coal tar enamel off a buried pipe. Polyethylene and polypropylene, which have lower frictional coefficients, are able to withstand such movements better.

Sulfides, acids, and alkalies cause excessive damage to protective membranes. Membranes are generally resistant to neutral salts occurring in groundwater and to solutions in the pH range of 6 to 9. Saturated solutions of calcium hydroxide, as may be derived from fresh concrete, have a pH of 13.

Tests of waterproofing and protective coatings can not be completely relied upon, as corrosion of organic membranes and coatings occur over a period of years, which cannot be exactly simulated in "accelerated" tests.

The corrosion of an organic surface diffuses into the material, increasing deterioration. These surfaces are not normally affected by stray currents in the ground, because they are electrical insulators.

The relation between adhesion of the protective coating and longevity of the material is unknown. Coatings whose initial adhesion to the substrate was good have been known to fail. Experts have stated that a priming adhesive needs to be applied to carbon steel pipe before applying the coal tar enamel coating, although no such adhesive is generally used on concrete pipe.

TYPES OF MATERIAL

Although many materials are theoretically effective waterproofing membranes for concrete, some must be eliminated because of cost or limited availability. The following selected list of water proofing products are both commercially available and commercially priced.

Polyethylene

Polyethylene is available in sheet form 40 mils thick and can be welded to form a sheet of any size or shape. As an extrusion product, polyethylene has been used underground for over 25 years. DuPont, Union Carbide, Hercules, Koppers, Monsanto, and Dow are among the American firms who manufacture the raw material and sell it to processors, who form it into sheets and shapes.

Polyethylene is available in a number of density forms, divided into low, medium, and high density. The specific gravity varies from about 0.915 to 0.970. The lower density is amorphous and more flexible. The higher density is more crystalline and harder. Permeability to gases at 25°C varies as shown below.

Density	Nitrogen	Oxygen	CO_2	Water Vapor
0.92	1.6	5.6	25	1.2
0.94	0.65	2.1	7.4	0.2
0.95	0.45	1.5	4.3	0.2

Units: $X10^{-10}$ $Cm^2/s.$ cm Hg (difference) for gases

$X10^{-10}$ $g/Cm^2.$ cm Hg (Δ) at 90% R. H. at 1 mil thick

Although polyethylene is embrittled by sunlight, this is not important in tunnel waterproofing applications. Stressed polyethylene (especially high density) will crack when subjected to organic, polar substances (e.g.

acetone). At room temperatures, polyethylene is resistant to acids, alkalies, and sulfides. It is unaffected by oxygen in the absence of U.V. radiation. It is affected by halogens.

Polyethylene has very low water absorption and low moisture vapor transmission. It embrittles at -70°C and softens at 70°C. High density (formulated) grades retain utility at temperatures as high as 130°C.

The coefficient of linear expansion is about $1.8 \times 10^{-4}/^{\circ}C$ and creep is set at a maximum allowable strain of 5 percent. Low density polyethylene has a specific resistance of about 10^{17} ohm-cm. which adds to its protective capability.

Polyethylene of 0.92 density will have a tensile strength of 0.7 kg/mm^2 with an extension of 300 percent at break. Other properties are:

Property	At Low Density (kg/mm^2)	At High Density (kg/mm^2)
Flexural modulus	35	77
Flexural strength	11-14	17-24
Compression modulus	—	50
Compression strength	1.1-1.7	1.8-3
Hardness; Shore D	50-60	65-70

When the surface of a polyethylene sheet is first polarized by ozone or flame treatment, the sheet may be bonded to other surfaces with epoxy or other adhesives.

Hypalon

When polyethylene is chlorosulforated, a rubbery product called Hypalon is formed (manufactured by DuPont). By vulcanization, a tough, chemically-resistant rubber is obtained. Vulcanization may be accomplished at room

temperature. The specific gravity is about 1.2; the thermal conductivity is 2.7×10^{-4} cal./cm.s.$^{\circ}$C. The brittle point is -60°C and the maximum service temperature is 120°C. Specific resistance is 10^{14} ohm-cm and tensile strength (hardness 65-IRHD) is 0.93 with 500 percent extension at break.

Hypalon, as have other elastomers, has been employed as a pit on pond liner and installed by the Watercover Co., Inc. Promotional material attached. See also Flexseal of B.F. Goodrich.

Polyvinyl Chloride

The only product, definitely known to this report, used as a waterproofing membrane for concrete is called T-Lock Amerplate and is manufactured by Ameron Corrosion Control Division. It has been used in this type of application since 1948.

Polyvinyl chloride or PVC is a tough, horny, and hard material. To obtain flexibility, a chemical plasticizer like DOP is added; and so the properties of the finished product depend upon the ultimate composition. The properties of T-Lock Amerplate are described in the attached brochure. For similar applications, Koroseal Lok-Rib is also a suitable system.

Qualitatively, PVC is chemical resistant and water resistant. Its water absorption is slightly higher than that of polyethylene as is the moisture vapor transmission. It is very resistant to biodegradation and to sulfides, acids, and alkalies. Its solvent resistance is less than that of polyethylene.

The specific gravity of plasticized PVC is about 1.1-1.5. Water absorption of plasticized PVC at 50°C for 48 hours is 0.6 percent. MVP for 20 percent plasticized PVC is about 10^{-10} g/cm.s. cmHg (Δ) at 30°C.

Coefficient of linear expansion is about $2.5 \times 10^{-4}/^{o}C$. Flexibility is retained to about $-50^{o}C$ and serviceable to about $60^{o}C$. The electrical properties of both plasticized and rigid PVC are comparable to polyethylene. The hardness of plasticipzed PVC (shore A) is about 75.

Butyl Rubber

Butyl rubber is a soft product often used as an adhesive for a harder backing, because butyl rubber has a strong tendency to cold flow and is able to fill in crevices and act against the capillary travel of moisture. Butyl rubber is unaffected by oils and dilute solutions of acids, alkalies, and salts. It has good resistance to oxygen and to the permeation of water.

The specific gravity of butyl rubber is 0.91 to 0.96. Water absorption after 7 days at $100^{o}C$ is 2.9 percent. Permeability at $25^{o}C$ to O_2 is 1.3×10^{-10} $cm^2/s./cmHg$ '; CO_2, 0.3×10^{-10}. To H_2O, 0.03×10^{-10} $g/cm^2.s./cmHg^{\Delta}$. Thermal conductivity is 3×10^{-4} $cal/cm.s.^{o}C$. The coefficient of linear expansion is $1.8 \times 10^{-4} cm/^{o}C$. The brittle point is about $-65^{o}C$. The electrical resistance is about 10^{17} ohm-cm. The tensil strength is high, as is the abrasion resistance.

Neoprene

Neoprene resembles natural rubber in properties. Neoprene, because it is chlorinated, is resistant to burning and to biodegradation. Neoprene is available prevulcanized or it may be vulcanized in place. Its specific gravity is 1.20 to 1.25.

The permeability to oxygen of neoprene is about 3.9×10^{-10} $cm^2/s./cmHg^{\Delta}$ and to water, about 1×10^{-10} $g/cm.s.\ cmHg^{\Delta}$. Mechanical properties of Neoprene vary with the fillers used and the degree of vulcanization. However, as an average, the following apply:

Property	Measurement
Elastic modulus (statis)	0.2 kg/mm^2
Tensile strength	1.3-2.2 kg/mm^2
Coefficient of linear expansion	$2.4 \times 10^{-4}/^{\circ}C$
Brittle at	-40 to $-70^{\circ}C$
Specific resistance	10^8 ohm-cm

When fully vulcanized, neoprene can reach the hardness of ebonite. When vulcanized to the hardness of a rubber heel (Shore A-45), with time, the hardness increases to reach a brittle product. This would be true for any polymer that is capable of being cross-linked three dimensionally.

Miscellaneous

There are other variations of polymeric materials used as waterproofing materials, but experience of these products in use is limited. Nordel, manufactured by DuPont, is an ethylene-propylene elastomer. Its chemical properties are similar to polyethylene. Its specific gravity is 0.86. Its chief advantage is its improved weatherability and resistance to elevated temperatures, although it has only been successfully buried in the earth for a few years.

A second type of material is chlorinated polyethylene, which is obtainable as a rubbery sheet. Its outstanding feature is its improved resistance to sunlight and weather.

Coal Tar Enamel

Coal tar enamel is fully described in AAWAC-203-73. Multiple-application fiberglass reinforcing mats are recommended for the inner plys but impregnated felt should be used for the two outer plys.

The application of a built-up membrane waterproofing to a roof or horizontal surface is common; however, such an application to vertical surfaces will encounter the problem of sagging of the hot coal tar unless carefully done.

The procedure to follow for both vertical and horizontal surfaces in application of the membrane is to allow the concrete to age for 28 days and then lightly sandblast the surface and blow it clean with air.

Apply from 1/32-inch to 2/32-inch of hot coal tar pitch and then apply over this a layer of felt impregnated with coal tar pitch (15 pounds per square). The overlap of the impregnated felt should be about 1 inch. Another application of coal tar and another impregnated felt should be followed by a third to provide maximum protection.

To prevent the pitch and felt from sagging, the application should be done in sections. When one section has been completed, say a width of 5 feet, this section is backfilled. Another section is then applied and backfilled. This is continued until the whole is complete. Another strategy is to externally secure the tarred felt to the concrete wall to prevent excessive sagging until backfilling is complete.

A protective shield should be placed in accordance with the best practice; but it is suggested that this outer layer of concrete be locked to the main structure of concrete for stability prior to backfilling.

Coal tar applications should last over 100 years.

Bentonite Panels

Bentonite panels are high sodium mineral bentonite (90 percent montmorillonite and 10 percent volcanic ash) packed in corrugated sheets

of biodegradable kraft panels, approximately 1/4-inch total thickness. The panels are generally glued or nailed to the walls and roof of the subway structure. Generally no protection against mechanical damage beyond a layer of sand of the roof is provided. After backfilling, anaerobic action degrades the kraft containers leaving an inorganic bentonite water barrier which has been activated into gel by moisture in the soil, which effectively seals off water penetrating the structure.

According to the manufacturer, the longevity of the bentonite is unlimited since the components are of clay. Once hydrated, the sealing effect remains over the years. If dried and again wet, the gel resumes its earlier consistency. The bentonite gel may seal cracks up to 1/4-inch, and the water does not leach out the gel once the flow of water has started.

The minimum amount of water required for the hydration of bentonite is four times its own weight. The swelling during hydration depends on the pressure the panel is subjected to. The swelling is 40 times its dry volume under zero pressure. The bentonite has a zero swelling under pressure of 28 psi.

High pH values in connection with certain chemicals, such as sulfides and gypsum, are harmful to bentonite. Also alkalies and brines may be harmful in certain combinations.

Bentonite is not affected by frost action. The sealing effect resumes when the bentonite gel, together with surrounding soil, thaws.

Bentonite gel is an electric conductor so that a subway structure waterproofed by bentonite panels is not shielded from externally or internally generated stray current.

Bentonite panels may also be applied to the interior face of excavation supports before structural concrete walls are poured. The face must be be bent to conform to the shape of the excavation support walls.

COMPARATIVE COSTS

Synthetic Materials

The material cost per square foot for the various types of synthetic waterproofing, assuming large quantity purchase in mid-1976, is:

Material	Cost/ft^2
Polyethylene, 30 mil	$0.36
Hypalon, 30 mil	$1.70
Polyvinyl chloride, 30 mil	$0.45
Butyl rubber, 30 mil	$0.55
Neoprene, 30 mil	$1.10
Polyethylene/butyl, 30/30 mil	$0.80

The cost for installing the membrane is approximately the same for all materials but varies with the type of surface between $0.25 and $0.50 per square foot.

Coal-Tar Enamel Built-up Membrane

The cost of the material and its installation for the average cut and cover structure is approximately:

Type of Membrane	Cost/ft^2
3 ply	$1.60
5 ply	$2.00

Bentonite Panels

Cost of the material and installation for bentonite panels is approximately $1.25 per square foot.

Protection of Membranes

Protection of membranes is accomplished by 2-inch concrete slabs (horizontal) at $0.40 per square foot, 3/8 inch plywood (walls) at $0.80 per square foot, or 3 inch concrete blocks (walls) at $1.80 per square foot.

Appendix F

LABORATORY SEALANT TESTS FOR SUBWAY TUNNELS

INTRODUCTION

The following precis of a December 1968 report on Subway Tunnel Sealant Tests describes laboratory testing work done by Bechtel Corporation on sealant systems, embodying epoxy resin adhesives and other materials for use in the subway tunnel caulking grooves.

The testing work was performed by Hales Testing Laboratories, Oakland, California. The testing programs and direction thereof, and the preparation of the report, were undertaken by Bechtel Corporation, San Francisco, for the Joint Venture of Parsons Brinckerhoff-Tudor-Bechtel which was acting in its capacity as engineering consultant for the San Francisco Bay Area Rapid Transit District. Unless indicated otherwise, the contents of this report and the conclusions stated herein represent the professional judgment of Bechtel Corporation as to the matters coming within the scope of its assignment. The work covered by this report was accomplished between December 1966 and December 1967.

SUMMARY

Four sets of test plates, each comprising two plates bolted together with caulking grooves of dimensions similar to those provided in the tunnel segments machined along the perimeters, were used to test and evaluate two sealant systems, see Figure F-1. After the sealant systems had been installed in the caulking grooves, water was introduced under pressure between the plates and the width of the grooves was expanded in

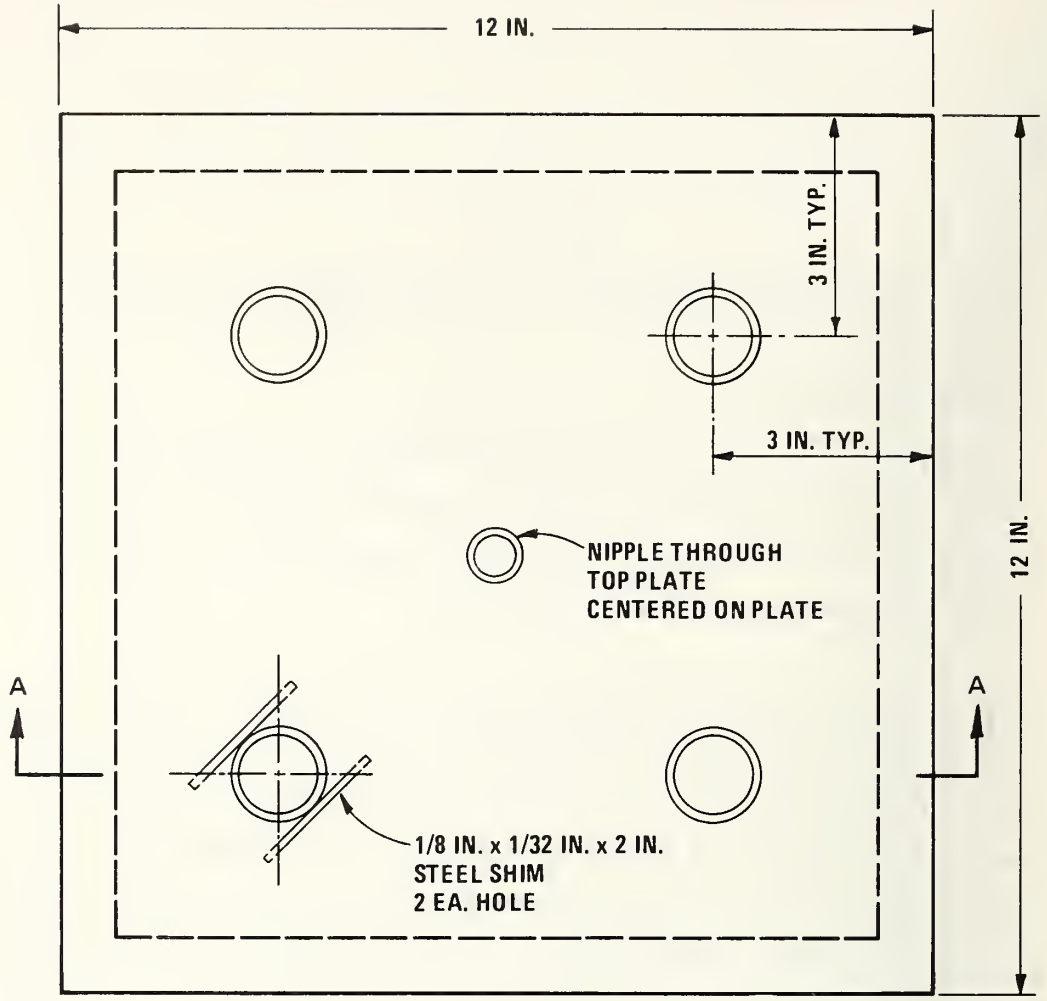


Figure F-1. TEST PLATES FOR EVALUATING TWO SEALANT SYSTEMS

incremental amounts to simulate the physical service conditions that would apply in the caulking grooves of the erected tunnel lining.

To establish the bond strength of the epoxy adhesives to inorganic zinc silicate coated surfaces and to neoprene, and also to ascertain the elasticity of the adhesives and sealant systems, small contact plates were used between which epoxy adhesives were installed and tested. On most of the adhesives that were considered, standard tensile bars were prepared and tested for tensile and elongation properties.

Details of these tests are contained in the Hales Testing Laboratories' Reports, copies of which are available.

The two systems tested were:

1. A sealing yarn comprising a core of hydroscopic and expansive material contained in a fiberglass sheath caulked into the root of the groove; the remaining groove space was filled with an epoxy adhesive
2. A neoprene sealing strip bonded within the groove with an epoxy adhesive

As the testing progressed, it was found desirable to modify the materials and the method of installation of both systems. The systems finally established performed satisfactorily in the tests and were recommended for installation and further evaluation in 50 feet of erected tunnel lining.

The details of undertaking such a test installation are included, and an indication is given of probable cost savings by substituting one of the systems for the presently specified lead caulking.

Test Criteria

The criteria for the testing of the sealant systems were established from considerations of the installation and performance requirements of the sealant in the subway tunnels. These included:

> The sealants were to resist 45 psi water pressure (80-foot heat of water) as the 5/16-in. wide caulking groove was opened 0.01 inch. This was the equivalent of a 3 percent movement across the groove
>
> All metal surfaces containing sealants were coated with inorganic zinc silicate, according to the tunnel segment manufacturing specification, and the surfaces were coated with a 5 percent silt 95 percent water solution prior to installing the sealant
>
> The sealant systems were to demonstrate that they can be installed readily in vertical and overhead positions and not sag prior to "setting up"

Sealant Systems and Materials

The following sealant systems were tested:

1. Epoxy adhesive extruded into the groove
2. A yarn consisting of a core of expandable material, in the presence of water, within a fiberglass sheath caulked into the root of the groove. The remaining exposed groove space was then filled with an epoxy adhesive to hold the yarn in place under water pressure
3. A neoprene strip bonded in the groove with an epoxy adhesive that was compatible with both the neoprene and the zinc-coated groove surface

The epoxy materials used in the various systems are listed in Table F-1.

The yarn consists of an oakum core filler combined with a hydrous magnesium silicate contained in a braided fiberglass jacket. It is described as acid resisting.

Table F-1

SEALANT SYSTEMS AND MATERIALS

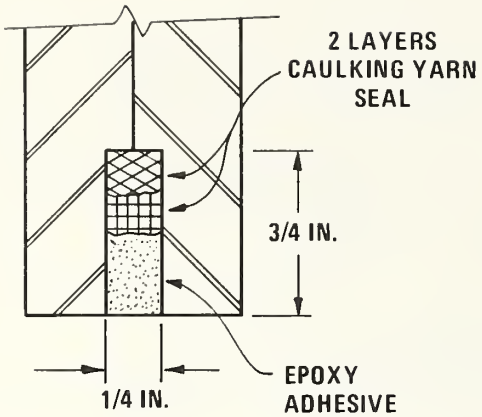
System	Material	Supplier
1 and 2	Concresive #1078, D1168, D1168-1, D1168-2	Adhesive Engineering Co. San Carlos, California
1, 2, 3	Tereco #410, Parts A and B	Tereco Seattle, Washington
2	Caulking yarns: White Oakum #310, 5/16-in. dia.; White Oakum #110, 5/16-in. dia.; Structural #420, 5/16-in. dia.	Sealite Inc. San Leandro, California
3	Concresive D1168-1, D1168-2	Adhesive Engineering Co.

Several cross sections of Neoprene were tested for System 2, as indicated in Figure F-2, and were:

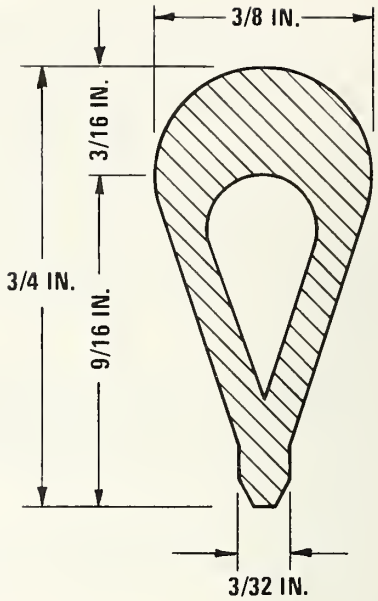
Materials	Supplier
Neoprene Sheets N3S (various thicknesses)	Gaco Western, Inc. California
3/16" x 5/8", 5/16" x 5/8", 1.4" x 11/16", 3/16" x 3/4", 1/16" x 1-1/2"*	Pacific Coast Rubber Co. California
Neoprene Extrusions Type 1253, Type 1561	

*The 1/16" x 1-1/2" sheet was folded by the laboratory with the edges bonded together with adhesive to produce a hollow "tear drop" section.

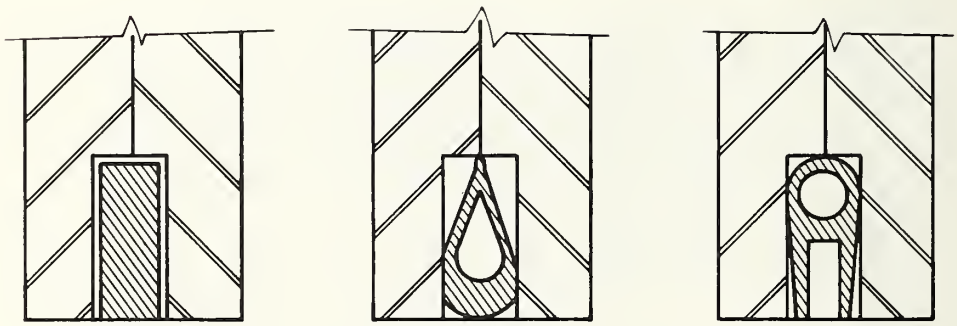
The sheets and the extrusions had a Shore A hardness of about 65. The sheets had a relatively rough suede surface treatment while that of the extruded sections was smooth.



CAULKING YARN
WITH EPOXY
SYSTEM 1



DETAIL OF ADOPTED
NEOPRENE EXTRUSION



NEOPRENE SEALS WITH EPOXY ADHESIVE
SYSTEM 2

Figure F-2. NEOPRENE SEALS WITH EPOXY ADHESIVE

Testing Procedures

Installation. In all the tests, a water/silt solution was first applied to the caulking groove. The various systems were installed and a period of at least 72 hours elapsed before testing.

Testing. Water was introduced between the two plates in increments of 15 psi to 45 psi. After each increment, the caulking groove was sucessively expanded in separate tests along the four edges with set-screws, provided for the purpose, about .004 inch at a time or about 1.20 percent of the actual 5/16-inch gap. The tests were halted when the sealants leaked continuously or when the expansion of the plates reached 0.025 inch (or about 8 percent of the gap).

Test Results. In System 1, the epoxy failed in bond, one side or the other, at about .04 inch, accompanied by severe leakage at all of the three pressure stages.

In System 2, leaks sometimes started at an early stage of expansion, when the epoxy "keeper" failed in bond. In these cases, the expansion was halted and after an hour or so the yarn expanded, the leaking stopped, and the incremental expansion was resumed. In general, the joint retained water satisfactorily at an expansion of .020 inch (about 6 percent) and a water pressure of 45 psi. White Oakum #110 (later designated BART #420) was formulated to provide maximum swelling produced the most satisfactory results.

In System 3, after some initial testing of seal configurations 1 and 2, the clothes peg (3) which appeared to provide the most positive seal was tested for various methods of installation.

The best method was to place epoxy in the root of the groove coating and the seal with epoxy before inserting it in the groove. Generally the groove

could be sealed against 45 psi with expansions up to 0.015 inch (or 5 percent of the gap).

Conclusions. System 2 appeared to provide the most satisfactory elasticity and was less dependent upon the strict quality control than System 3 required in its installation. System 1 did not appear satisfactory for installation in grooves with expected large movement across the gaps or where freely running water was encountered through grooves during installation.

SEALANT TEST INSTALLATION

A test installation was made in BART Contract R0053, KR Tunnel, on January 6 and 7, 1968.

Adhesive Engineering, San Carlos, California, was responsible for providing the equipment for mixing and injecting the epoxy adhesives and for supervising the installation of the sealant systems. In addition, it provided some of the labor; the R0053 Contractor, Shea-Macco, provided the remainder.

Sealant Systems

The two sealant systems that were installed in the tunnel segment caulking grooves are described below:

> System 1. Two layers of Sealite #420 5/16-in. diameter yarn caulked into the groove and the remaining groove space filled with epoxy adhesive
>
> System 2. The groove was partially filled with epoxy followed by the insertion of neoprene hollow "teardrop" cross section strip

Two epoxy adhesives were used for each system. Adhesive Engineering D1168-2 and Tereco #410.

Approximately equal footages of the two systems with the two epoxys were installed in the circle and longitudinal caulking grooves of 11 rings proceeding from Ring #475 through #485 inclusive. The shield tail space had been pea gravelled but not grouted above the spring line; the ground had been dewatered and little water was present in the segment joints. However, when the installation was at rings #477-#478, circle interface water was introduced through a top grout plug of ring #478 and water flowed at a diminishing rate through the joints until ring #483 had been caulked. The joints of rings #478 through #483 inclusive could be classed as "wet," though the water flowing through the joints was not under a high head. In each ring the installations were made only above the temporary timber decking in the bottom of the tunnel, and generally the installation in one ring included four segments plus the key.

Details of the sealant systems and their position in the tunnel are indicated in Figure 5.4-3.

Description of Installation

The grooves were thoroughly cleaned with a compressed air jet.

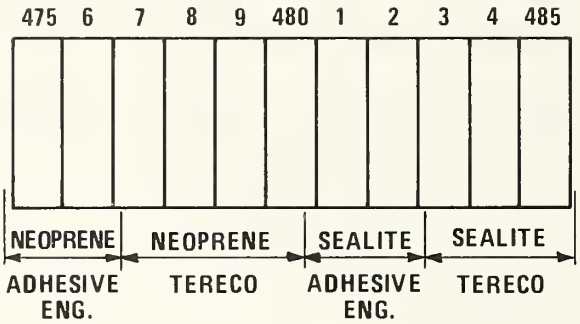
System 1. Two layers of yard were installed in the segment, see Figure F-3. Each layer was well compacted with a caulking tool.

The remaining portion of the grooves was cleaned of any powder with a water or air jet and the epoxy was placed.

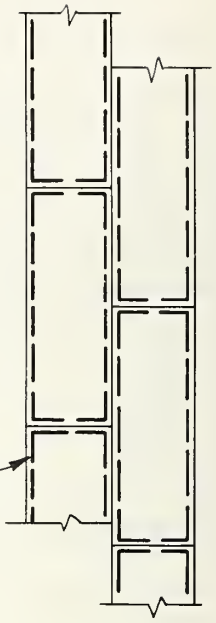
System 2. The epoxy was placed in the groove followed by the neoprene strip.

To evaluate the installations of the sealant systems under wet tunnel conditions, some of these were made after water had been introduced behind the tunnel liners (referred to previously).

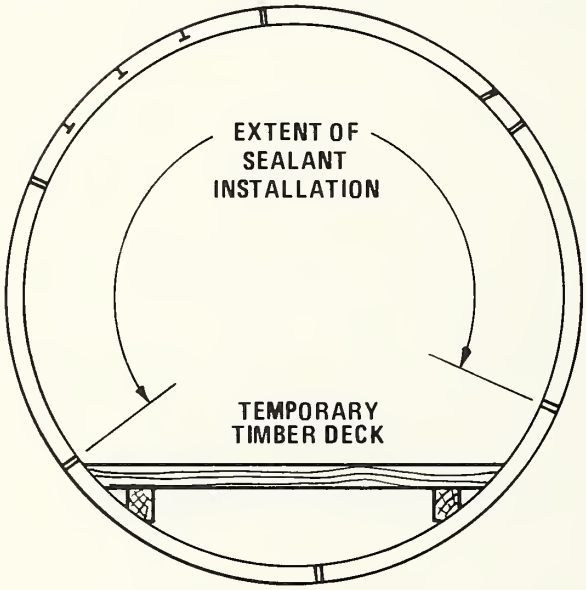
NEOPRENE



SEALANT SYSTEMS IN TUNNEL



SEALITE LAYER ARRANGEMENT



TYPICAL TUNNEL CROSS SECTION

Figure F-3. SEALANT SYSTEMS AND POSITIONS IN TUNNEL

Results

Some difficulty was experienced with the epoxy injection equipment which indicated modification would be required for future installations.

The neoprene cross-section appeared to be satisfactory, and its installation under reasonably dry tunnel conditions presented no difficulties. However, with the Tereco epoxy, after water was introduced and flowed through groove joints, apparent loss of epoxy viscosity caused some problems.

At the time of installation of neoprene with Adhesive Engineering epoxy, some water was flowing at a reduced rate through the joints, and there were no difficulties in making the installation and stopping the water ingress.

The installation of the sealite caulking yarn was straightforward once the correct width of caulking tool had been selected.

When water was introduced behind the tunnel liners, it was found that the flow through the joints could be effectively stopped by caulking the yarn into the grooves starting at the top of the tunnel and working down.

Inspections made 3 weeks after installation and subsequently (when ground dewatering had ceased and the water table was about 8 feet above the tunnel) revealed that the joints were satisfactorily dry.

Conclusions and Recommendations

It appears that both sealant systems have merit and may offer economies over the presently specified lead caulking, although some improvements in the epoxy injection equipment are needed. Both adhesives used appeared generally satisfactory, though some further modification to their nonsag and finish characteristics could prove beneficial.

The success of the sealite system depends more upon the degree of its compaction, which is a comparatively simple operation, and less upon the following epoxy. Therefore, this system may appear more attractive to the tunnel contractor wishing to undertake the caulking with his own forces. It is believed that comparatively little development work would be required to produce the equipment necessary for the economic and satisfactory injection of epoxy for the sealite system.

In respect of the neoprene system, if equipment was developed to coat the strip with epoxy, it would have the advantages of speed and simplicity and would seem to be the more economic of the two systems.

Appendix G

CATHODIC PROTECTION SYSTEMS FOR CUT-AND-COVER STRUCTURES

This is a summary of two reports by D. Seid of Research and Engineering, Bechtel Corporation.

A cathodic protection system for a cut-and-cover subway structure consists of rectifiers, anodes, anode junction boxes, reference electrodes, test stations, and miscellaneous hardware, such as cables, conduits, and connectors. The cost of a system for any particular subway depends on local soil conditions, width of right-of-way, and other factors.

The spacings of the anodes or anode groups could vary from 50 to 3,000 feet, the longest spacing usually being the most economical. However, to obtain uniform current distribution, the required distance (d) between the structure and the anodes increases with the spacing (s) between the anodes. When "s" is 200 feet, "d" is 20 feet; when "s" is 3,000 feet, "d" is 300 feet. A distance of 300 feet from structure to anodes is difficult to achieve in congested areas and these physical restrictions may require the anodes to be close to the subway structure. To evaluate the feasibility of a cathodic protection system, two examples are discussed with anode spacings of 200 feet and 3,000 feet. A cut-and-cover subway structure of 10 miles is used as a model in both examples, including stations every 1,000 to 3,000 feet. The two spacing examples are shown in Figure 5.8.

The cathodic protection system is sized primarily to protect the outer layer of the steel rebars in the concrete subway structure. The inner

layer is electrically shielded from receiving current from the outer layer. The outer layer is the most critical layer, since the corrosion attack starts from the wet outside surface.

On concrete subway structures, stray dc current pickup is the most hazardous for steel and it accelerates corrosion problems. Ac current produces approximately one percent as much damage as stray dc current of the same amperage. Possible sources of dc current are nearby public transportation systems, such as streetcars and rapid transit systems, dc transmission systems, high ampere ac transmission lines, and other cathodic protection systems. Some utilities, such as gas lines and liquid hydrocarbon pipelines, are required by law to have cathodic protection systems for corrosion protection, and it is becoming increasingly common for other utilities to be furnished with those systems as well. Where two or more systems cross each other or run parallel, the interferences have to be analyzed and resolved, either by making cross connections to make the systems work together, or by relocating the anodes. In these examples interaction problems have not been considered. The total system is shown in Figures 5.8 and G-1. The details of the system are shown in Figures G-1, G-2, and G-3. Quantities for each example are presented for estimating purposes.

Anodes (see Figure G-2)

1. Anodes shall be durichlor type D (2 inch diameter by 60 inches long) with epoxy encapsulation and Raychem thermofit anode caps.
2. Anodes shall be prepackaged in a 22 gauge sheet steel canister (10 inch diameter by 7 feet long) with end caps and lifting holes or straps on head of canister.
3. The canister fill material shall be well tamped calcined petroleum coke breeze (1/8 inch by 3/8 inch particle size).
4. Anode lead wire shall be No. 8 AWG, stranded, copper, with high molecular weight polyethylene insulation.

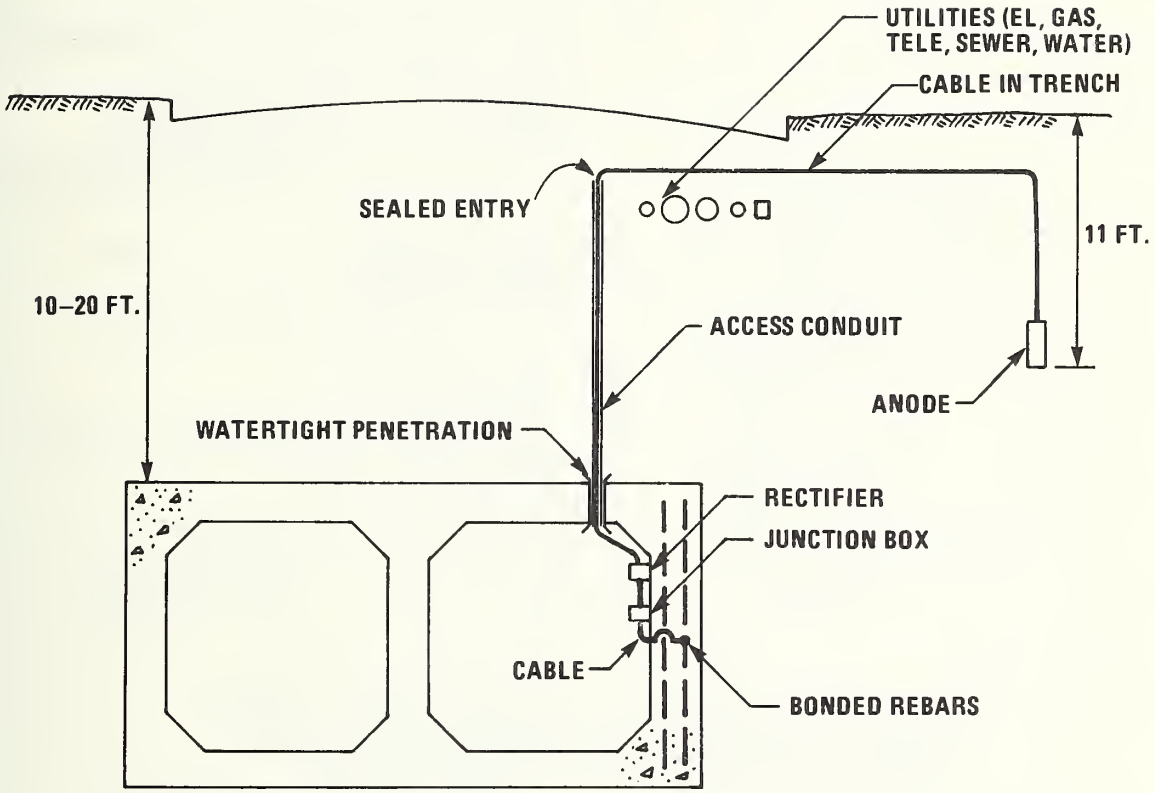
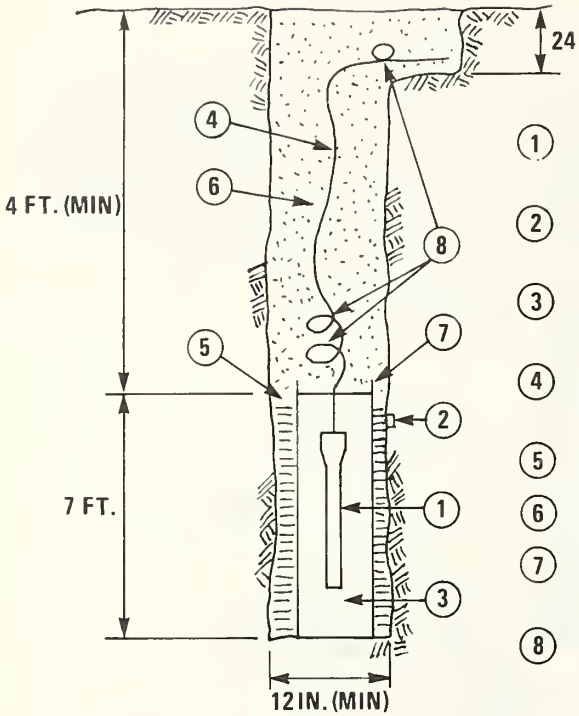


Figure G-1. CORROSION PROTECTION SYSTEM



1. ANDDE #1 DURICHLOR TYPE CD (1-1/2 IN. DIA. x 60IN. LONG) WITH EPDXY ENCAPSULATIDN & RAYCHEM SLEEVE.
2. CANISTER–16 GA. SPIRAL WELDED SYSTEM 10 IN. DIA. D.D. x 7 FT. LONG W/END CAPS.
3. BACKFILL–TAMPED COKE BREEZE PARTICLE SIZE 1/8 IN. x 3/8 IN.
4. ANODE LEAD WIRE – #8 AWG STR. COPPER, HMWDE INSULATION
5. BACKFILL–NATURAL SOIL WELL TAMPED
6. GRAVEL TD SURFACE
7. LIFTING HDLES–PROVIDE (2) 1/2 IN. DIA. HOLES IN HEAD OF CANISTER
8. 2 FT. SLACK LOOP IN ANODE WIRE

NOTES:

A. CAUTION–ANODE MATERIAL IS VERY BRITTLE, HANDLE WITH CARE DO NDT LIFT OR LOWER ANODE ASSEMBLY BY LEAD WIRE, USE LIFTING HOLES.

B. PDSITION TOP OF ANODE CANISTER 4 FT. MINIMUM BELOW GRADE

C. ANODE SPACING AS SHOWN ON PLAN. SEE DRAWINGS.

D. PLACE INDIVIDUAL ANODE LEADWIRES IN TRENCH A MIN. OF 2 IN. DEEP. CONTINUOUS WIRE FROM EACH ANODE TO JUNCTION BOX WITH NO SPLICES. PROTECT WIRES WITH WOOD COVER. COVER NOT REQUIRED IF TRENCH IS UNDER CONCRETE.

Figure G-2. SINGLE ANODE INSTALLATION

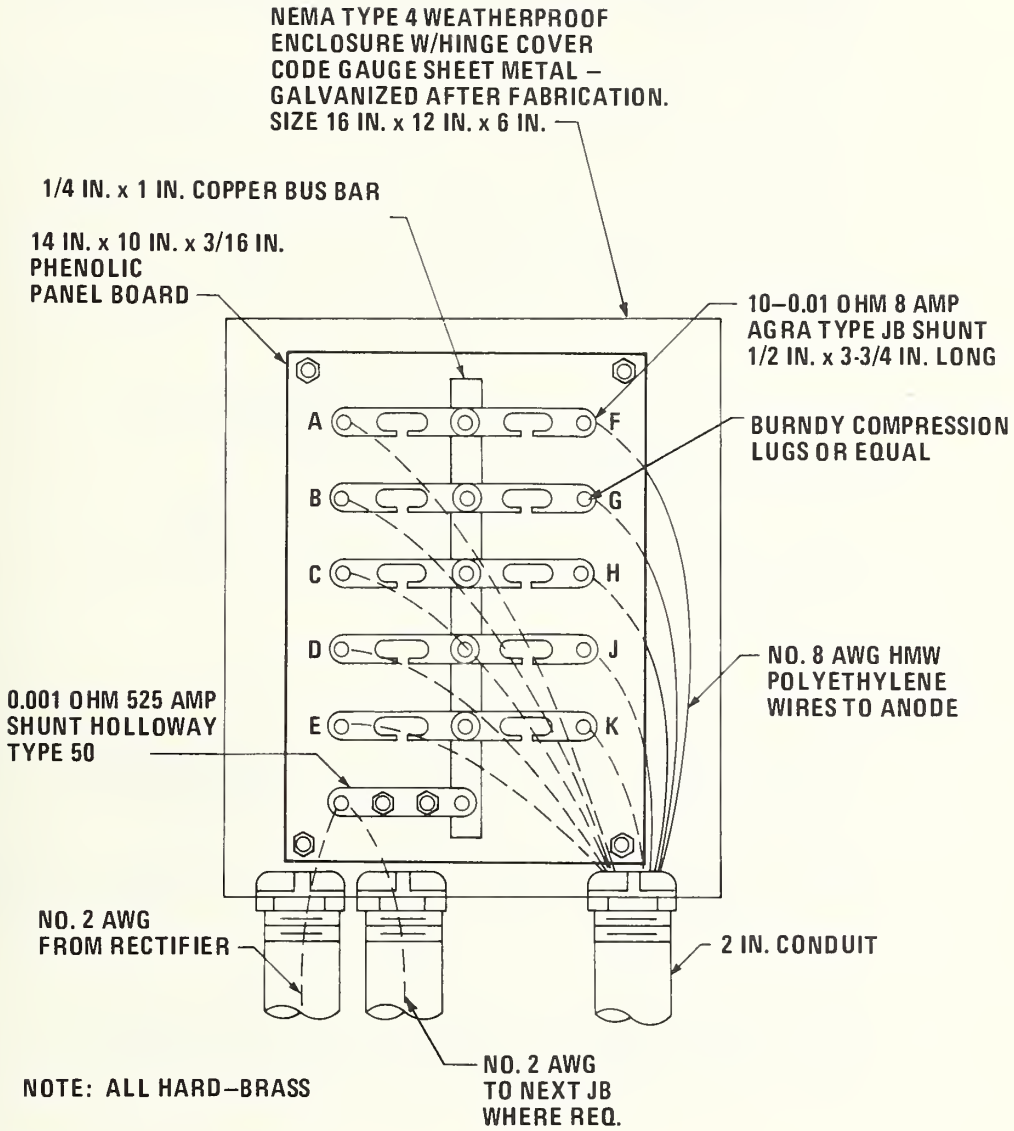


Figure G-3. TYPICAL JUNCTION BOX

Rectifiers

1. Rectifiers shall be capable of supplying continuous full-rated output at an ambient temperature of 45°C with an expected life in excess of 25 years.
2. Rectifiers shall be air-cooled by natural convection.
3. The output voltage shall be adjustable by means of not less than 20 equal steps.
4. Rectifiers shall meet the NEMA Standard MR-20-1958, "Cathodic Protection Rectifier Units," in addition to requirements of these paragraphs.
5. Rectifying elements shall be surge-protected silicon diodes.
6. The rectifier shall be equipped with an input circuit breaker, which shall hold 100 percent of rated load and must trip at 125 percent of rated load.
7. Meters shall have a minimum 3 inch scale length.
8. The transformer shall be of the separate primary and secondary type.

Anode Junction Box (see Figure G-3)

1. Enclosures shall conform to NEMA 4 Code for Indoor Installations and NEMA 3 for Outdoor Installations.
2. Anode junction boxes shall contain ten 0.01 OHM-8 ampere Agra type JB shunts for measuring currents to individual anodes.
3. All individual anode shunts shall be connected to a common bus bar.
4. The rectifier positive lead shall be connected to the common bus bar through a 50 amp-50 millivolt shunt.

Cables

1. All cathodic protection cables shall be stranded copper conductors with high molecular weight polyethylene type CP insulation.

2. Size: No. 8 AWG from anodes to junction box.

   No. 2 AWG from junction box through rectifier to rebar connection. The lead attachment to the rebar should be patched by coating (Bitumastic 50) to withstand corrosion.

Cable Trench and Plastic Pipe

1. Cable trench, see Figure G-4

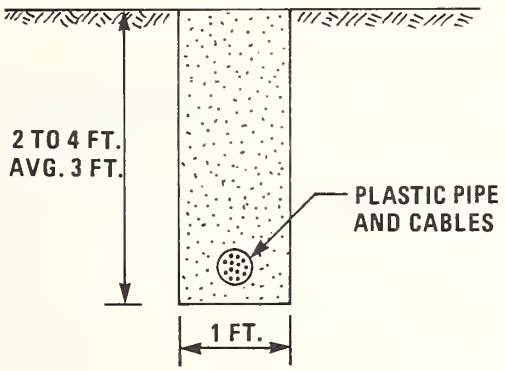


Figure G-4. CABLE TRENCH WITH PIPE

2. Depth as required to avoid utilities; minimum 2 feet.

Bonding of Rebar

1. The rebars in the structure shall be tack-welded together to assure electrical continuity
2. The electric continuity shall be carried through expansion joints, see Figure G-5 on following page.

Cable in Vertical Tube

1. The cables from the anodes shall be carried in trenches to a common spot above the structure and led through a vertical tube through the ground and the structure itself.

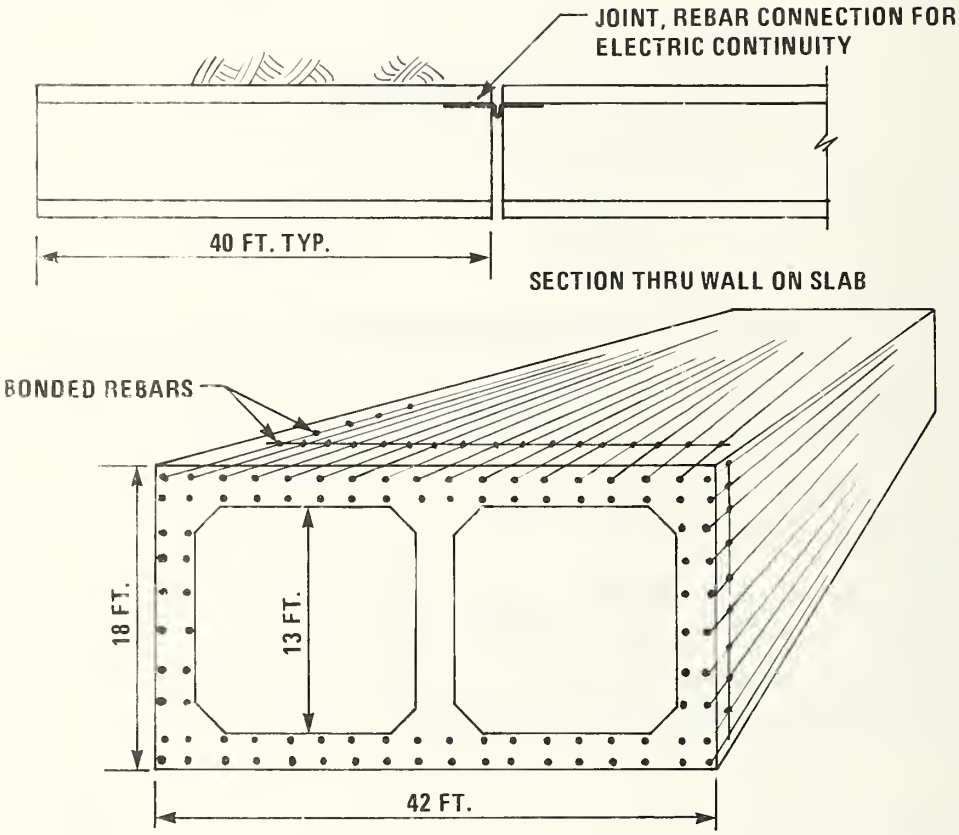


Figure G-5. BONDED REBAR

Reference Electrode (see Figures G-2 and 5-7)

1. Reference electrodes shall be Harco "Permacell" Underground Copper-Copper sulfate reference electrodes Model IHRP-802 or approved equal.
2. The reference electrodes shall be thoroughly saturated with water before backfilling.
3. Lead wires shall be No. 10 AWG with high molecular weight polyethylene insulation.

Test Station (see Figures G-6, 5.7, and G-7)

1. Test station junction boxes shall be Testox Type 105 (2 inch slip fit conduit size). It may be surface mounted as in Figure 5.6-8 or located within the subway as in Figure 5.6-7.
2. The reference electrode is introduced in a 5 foot deep hole, which is bored, has a 7 inch diameter casing, and accommodates two cables.

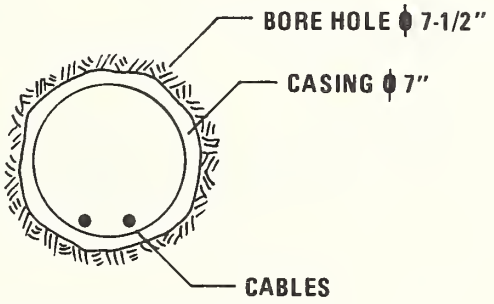


Figure G-6. ELECTRODE IN BOREHOLE

QUANTITIES FOR 10 MILES OF SUBWAY (52,800 FEET)

Example I. Anodes on one side of structure:

- Spacing between groups of anodes = 3,000 feet
- Distance between structure and anodes = 300 feet

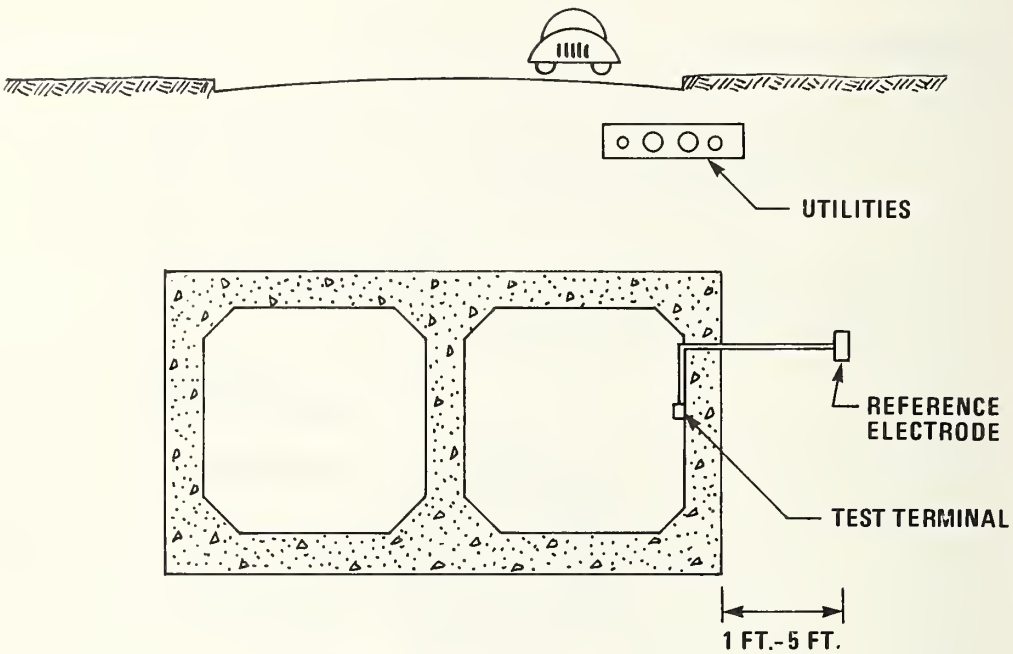


Figure G-7. CORROSION MONITORING SYSTEM

Item*		Unit	Quantity
1.	Anodes (52,800/3,000) = 18 groups x 20	—	360
2.	Rectifiers	—	18
3.	Anode junction box	—	18
4.	Cable No. 8: 18 x [20(205 + 300 + 10)]	Ft	185,400
	Cable No. 2: 18 x 10	Ft	180
5.	Cable trench 18 (400 + 300) including 4 inch plastic pipe	Ft	12,600
6.	Bonding of rebars 52,800/40 = 1,320 units		
	Per unit:		
	Walls 2 x 2 [(15.5/1.3) + 41/1.3] = 174		
	Roof and base 2 x 2 (40 + 41)/1.3 = 250		
	Total welds 1,320 (174 + 250) x 1.1 = 559.680	—	660,000
	"Carry trough" units	—	1,320
7.	Vertical conduits through ground and subway roof: 4 inch casing, 4-1/2 inch bore	—	18
8.	Reference electrodes	—	36
9.	Test station	—	36
10.	Replacement period of anodes	Yr	36
11.	Replacement period of other equipment, such as rectifiers, anode junction boxes, cables, plastic pipes, "carry trough" units	Yr	25
12.	Operation, supervision, etc. (adjust current, check rectifiers every month, replace failing units)	Men Per Year	1/4
13.	Power requirement (10 mile) 810 amp, 60 V, 70% effective 810 x 60 x 1/0.7 = 63,000 watts	kW	63

*Full description of items given in Details 1 through Detail 9.

Example II. Anodes on two sides of structure:

Spacing between anodes = 200 feet

Distance between structure and anodes = 200 feet

Item		Unit	Quantity
1.	Anodes (52,800/200) x 2	—	528
2.	Rectifiers	—	53
3.	Anode junction box	—	53
4.	Cable No. 8: (52,800/1,000)[(400 x 2 + 200 x 2) x 2 + 5 (20 + 20 + 40 + 20)]	Ft	153,120
	Cable No. 2: 53 x 10	Ft	530
5.	Cable trench: 53 x (2 x 400 + 80) = (including 2 inch plastic pipe)	Ft	46,640
6.	Bonding of rebars (as Example I)		
	Welds and patching	—	660,000
	"Carry trough" units	—	1,320
7.	Vertical conduit through ground and subway roof: 2-1/2 inch casing, 3 inch bore	—	53
8.	Reference electrodes, 2 x 53	—	106
9.	Test station	—	106

Appendix H

REPORT OF INVENTIONS

There were no patentable inventions or discoveries resulting from this work. However, the findings of this study, as reported herein, are improvements as they primarily assess subway maintenance problems and develop guidelines intended to alleviate these problems. Implementation of these guidelines by maintenance engineers can make a positive contribution to improved integrity and reduced maintenance cost of subway structures.

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